From Vermont to Hawai‘i: Monitoring Critical Design Features in Bioretention

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International LID Conference
Portland, Maine
August 29, 2016

research
green stormwater infrastructure

University of Vermont: Outdoor Bioretention Laboratory

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Portland, ME

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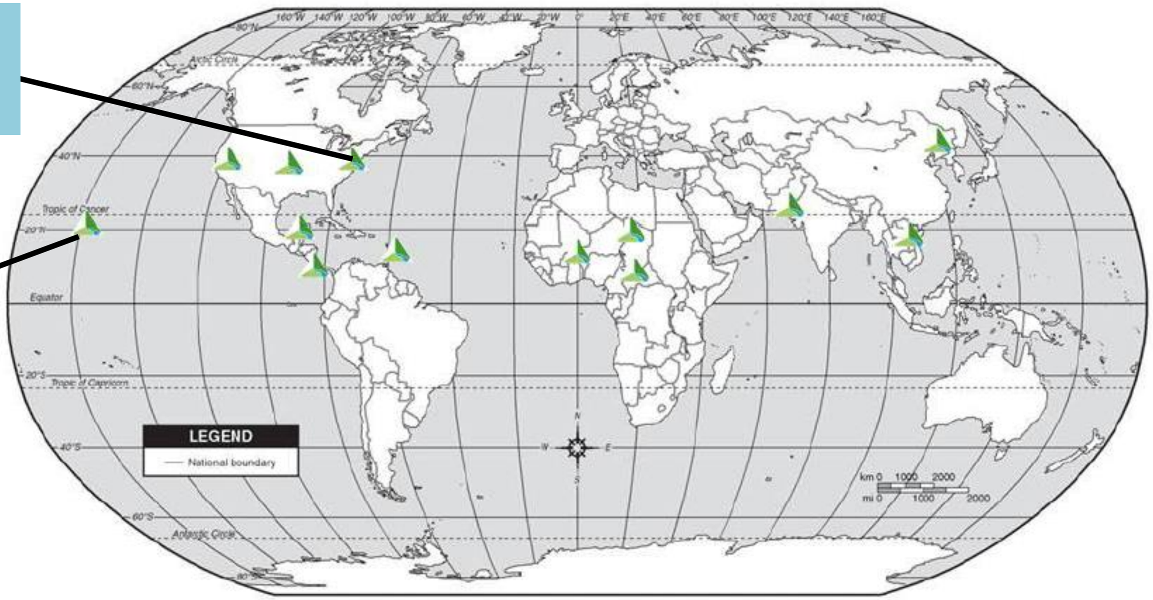

Global civil engineering firm specializing in LID, Research & Development, Construction, Operation & Maintenance

Residence – Akumal, Mexico

US Embassy – Ouagadougou, Burkina Faso

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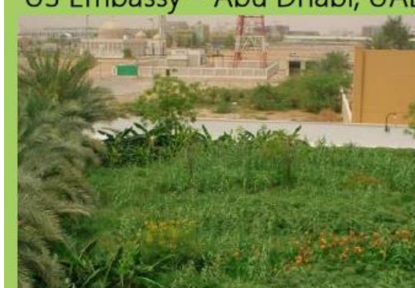


Urbanization Impacts
Local Hydrology and Water Quality

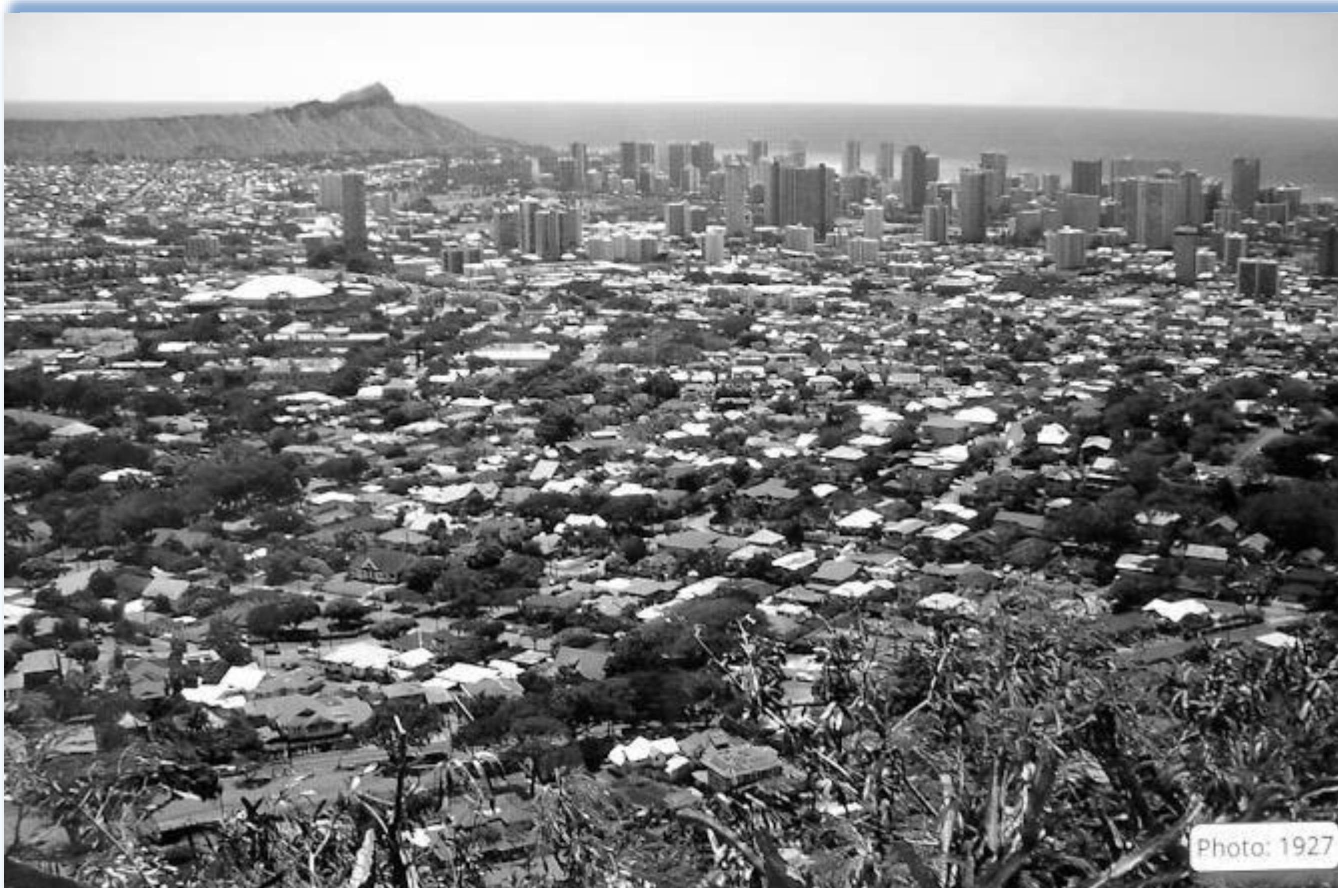
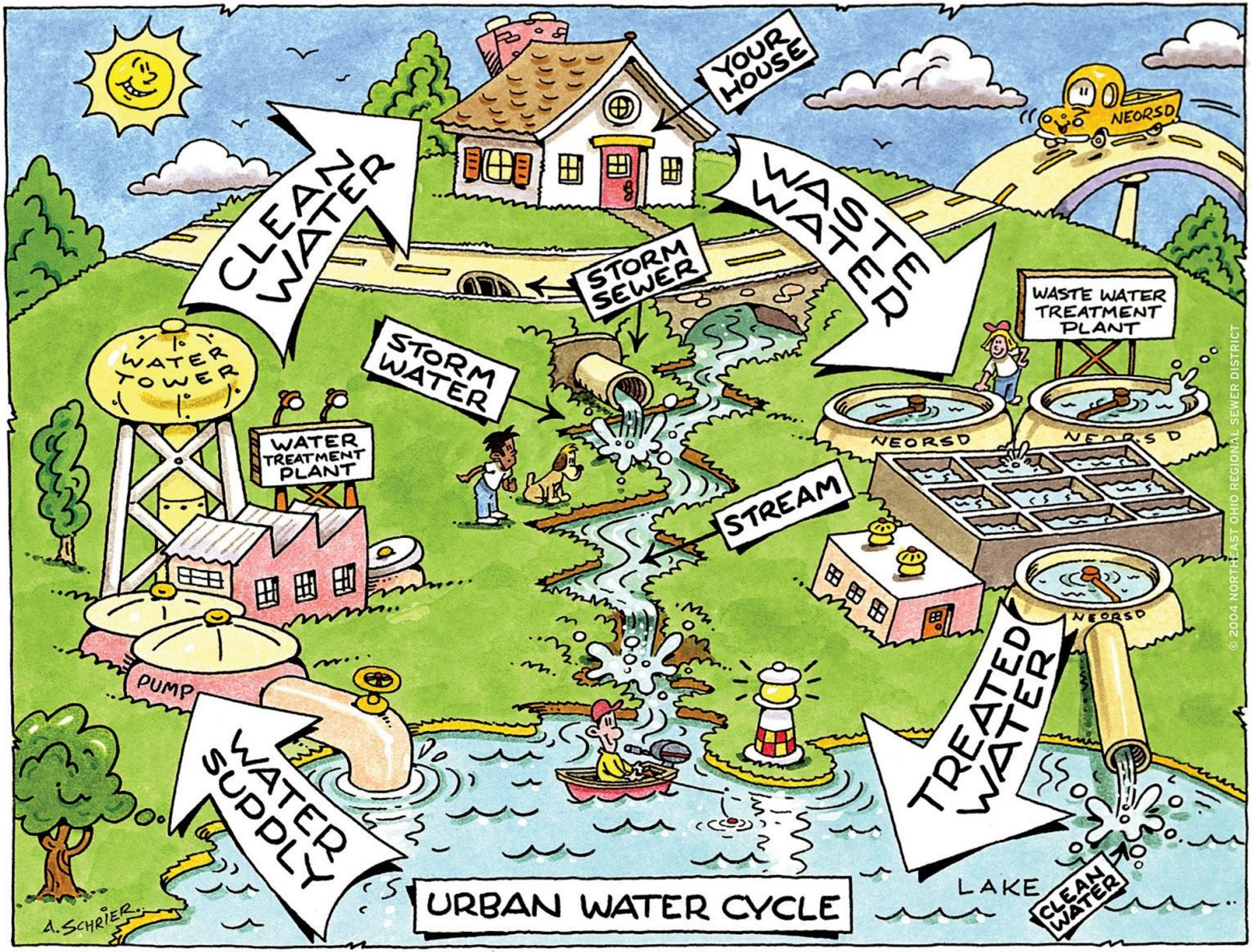
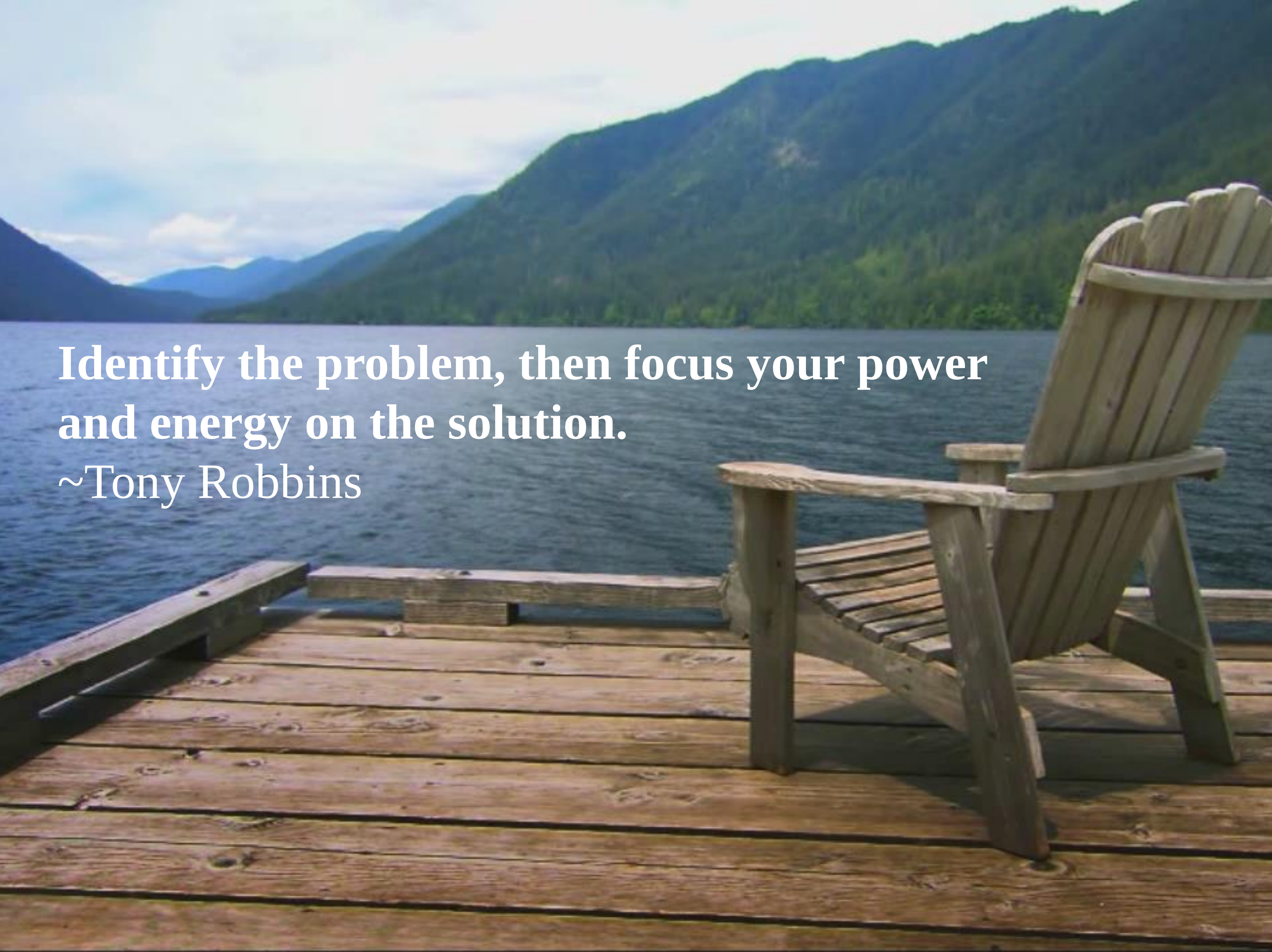


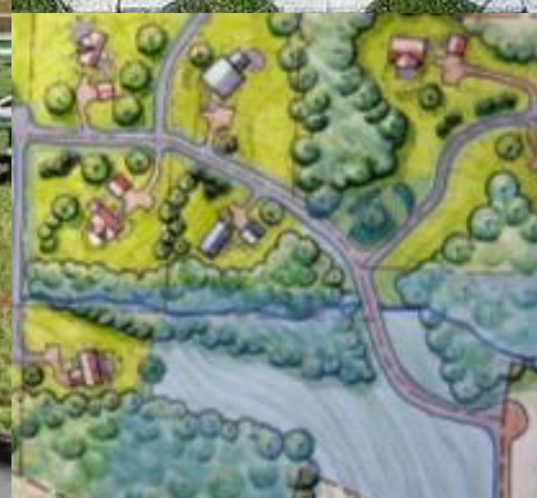
Photo Credit: Bernice Pauahi Bishop Museum


YOUR HOUSE
CLEAN WATER
WASTE WATER
NEORSD
STORM SEWER
STORM WATER
WATER TOWER
WATER TREATMENT PLANT
WASTE WATER TREATMENT PLANT
NEORSD
NEORSD
STREAM
NEORSD
PUMP
WATER SUPPLY
TREATED WATER
LAKE
CLEAN WATER
URBAN WATER CYCLE
A. SCHRIER
© 2004 NORTHEAST OHIO REGIONAL SEWER DISTRICT


Identify the problem, then focus your power and energy on the solution.
~Tony Robbins

Low Impact Design & Development

LID is an approach to development (or re-development) that mimics pre-development hydrology and uses ecological design and engineering to remove pollutants in stormwater and wastewater so it can be re-used or replenish groundwater supplies.

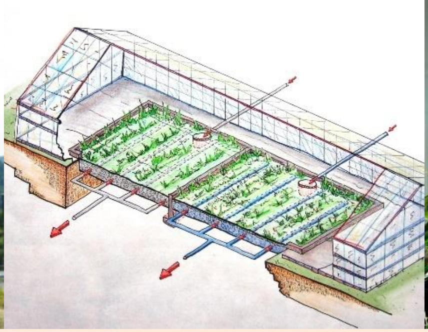


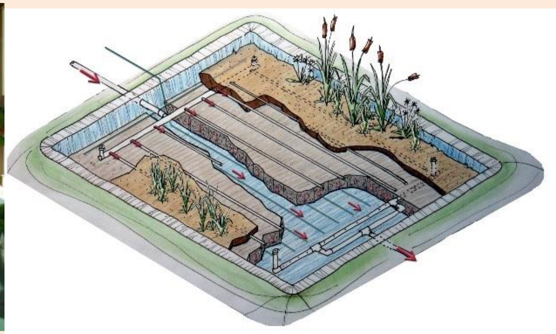
Decentralized Wastewater Treatment

Design Strengths:
Soluble Pollutant Removal
Provides Habitat
Increase Biodiversity
Efficient
Low Cost
Low Maintenance
Low Energy Consumption
Aesthetics (Functional Design)

Design Challenges:
Requires Maintenance

Image: Living Designs Group Inc.





Eco Machine for Wastewater Treatment:
University of Vermont

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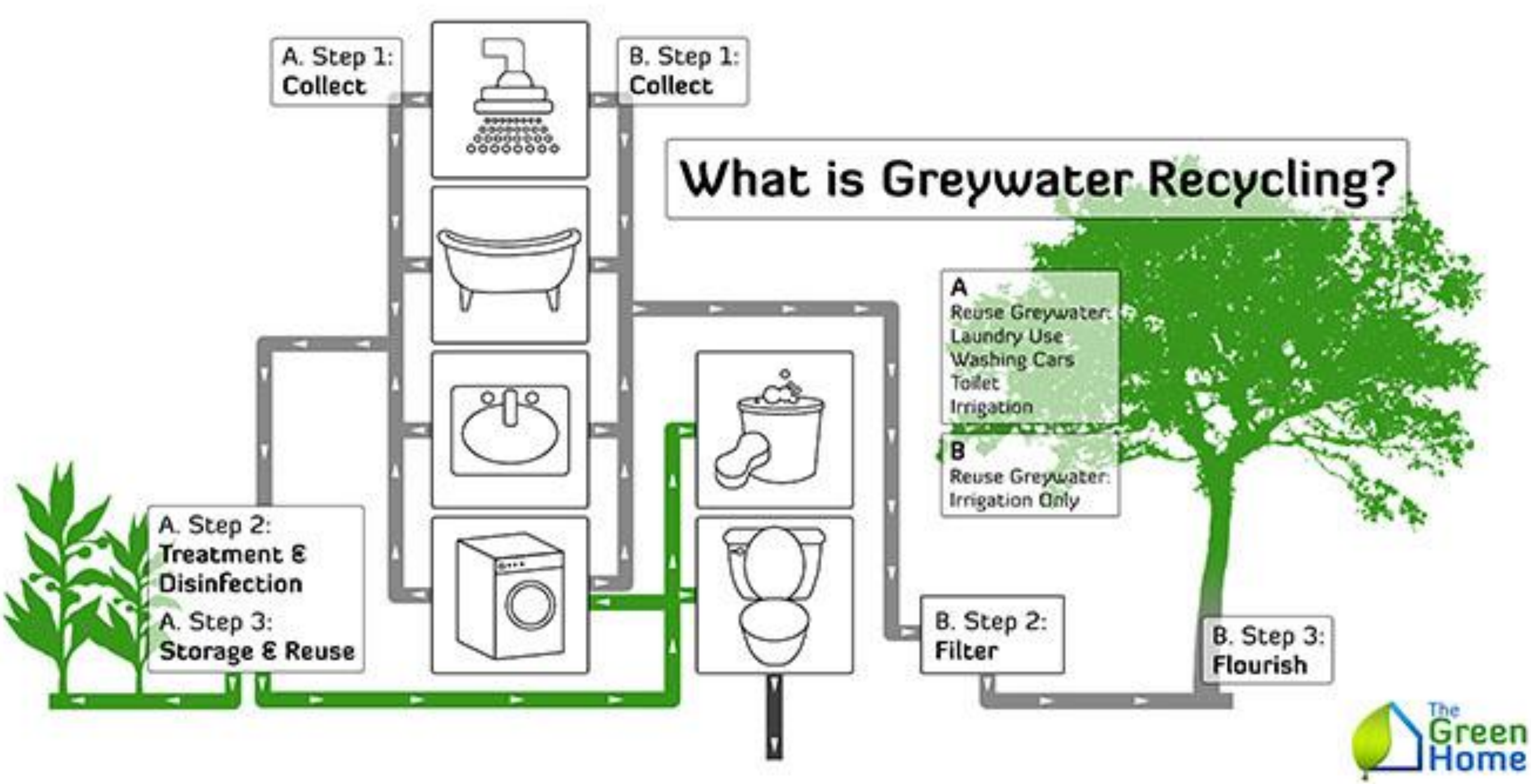
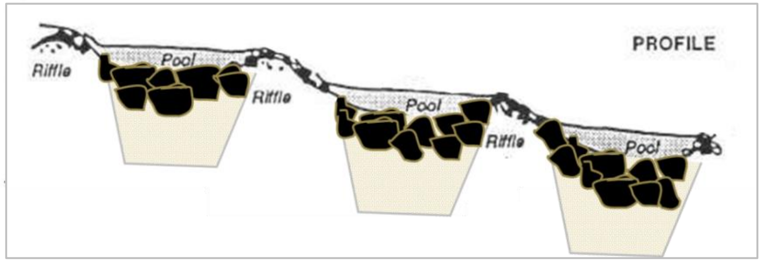
Gray Water Reuse



Forest Restoration and Natural Slope Stabilization

- Restoration of native forest
- Bank stabilization
- Naturalized rock check dams
- Reduction of peak flow rate
- Removal of sediment



Natural Swimming Pools

Design Strengths:
Decrease Chemical Discharge
Improved Human Health

Design Challenges:
Requires Maintenance





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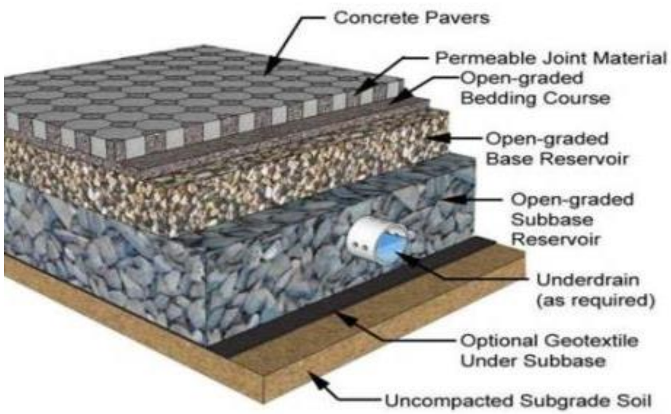
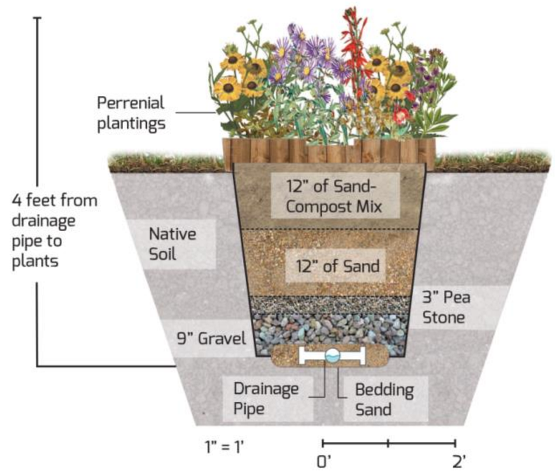
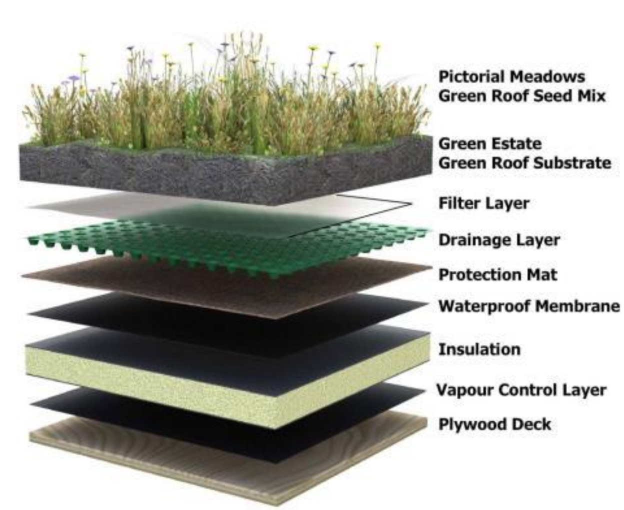
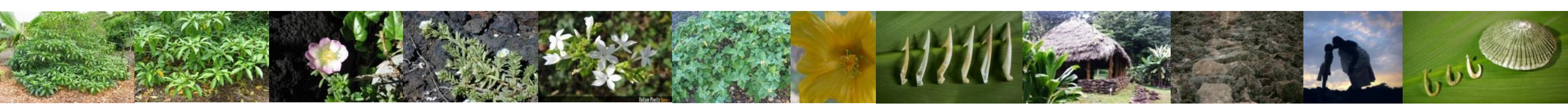
Low Impact Design and Development (LID) includes Green Stormwater Infrastructure (GSI)







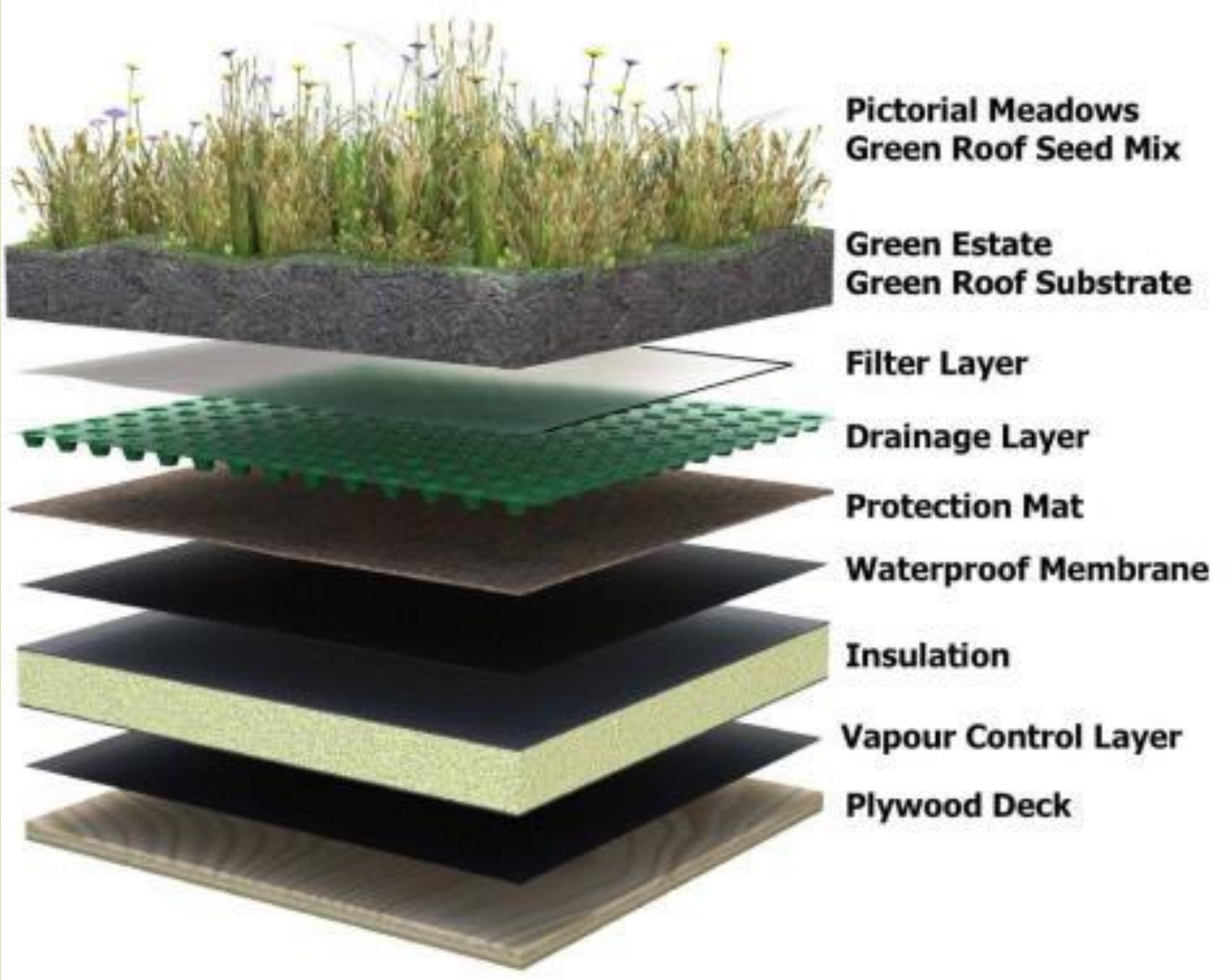


Davis 2008; Dietz and Clausen 2006; Zinger et al. 2013; Collins et al. 2010.

Green Roofs

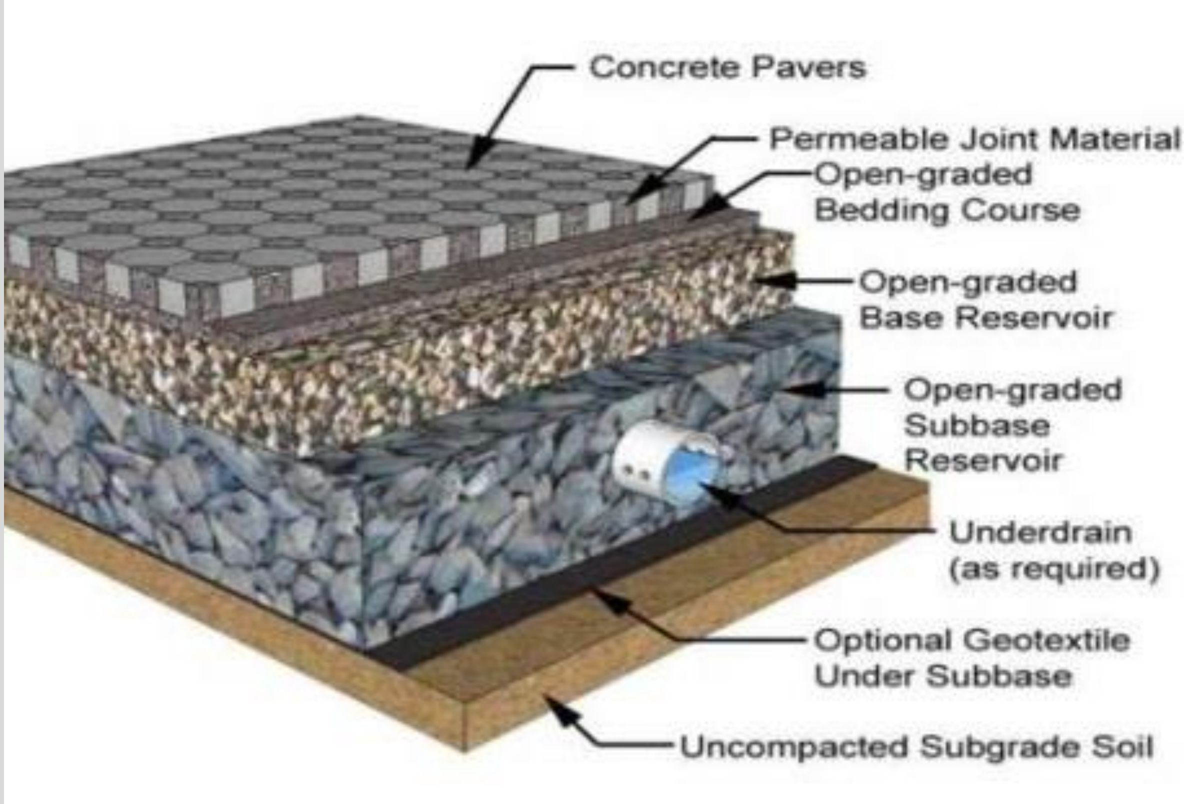
Design Strengths:
Reduce Volume
Reduce Peak Flows
Remove Pollutants
Reduce Temperature
Heat Island
Provide Habitat
Increase Biodiversity

Design Challenges:
Maintenance
Plant Selection



Green Roof:
Macy's Building Chicago

Porous Pavement



Design Strengths:
Reduces Storm Volume
Reduces Peak Flows
Particulate Pollutant Removal

Design Challenges:
Getting both strength and permeability
Protective buffer reduces siltation from offsite flows
Maintenance



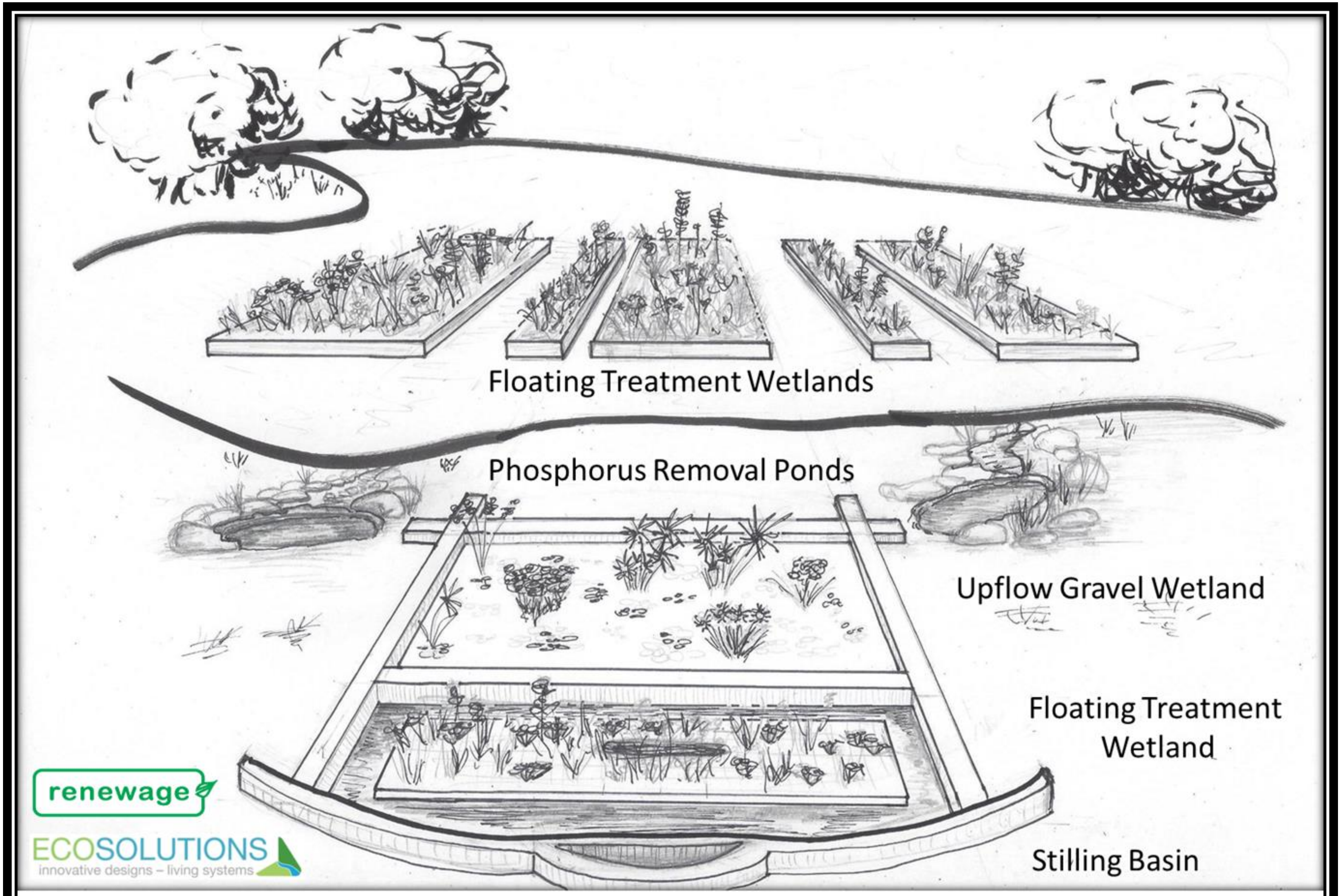

Technology Building
University of Hawaii

Floating Treatment Wetlands

Photo Credit: Floating Islands International

Design Strengths:
Nutrient Removal
Provides Habitat
Increase Biodiversity
Moderates Wave Action
Reduces Shore Erosion

Design Challenges:
Maintenance Logistics


Floating Treatment Wetlands
Phosphorus Removal Ponds
Upflow Gravel Wetland
Floating Treatment Wetland
Stilling Basin
renewage
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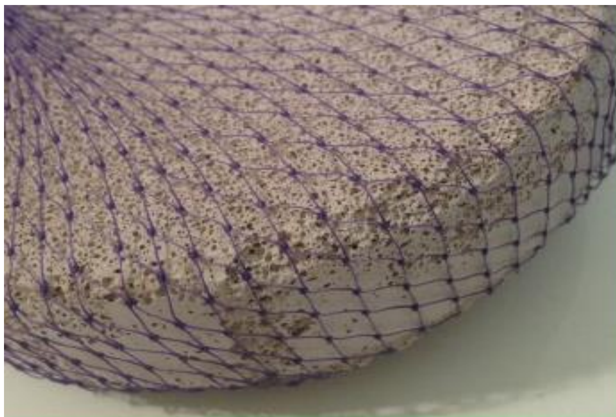

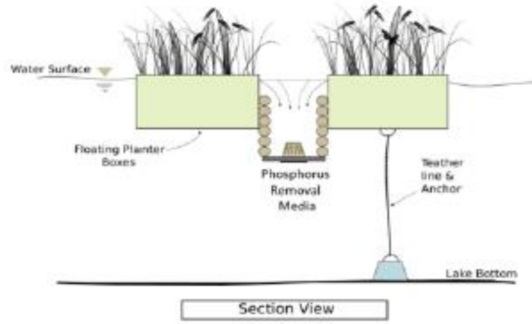

NORTH BEACH, VERMONT

RESEARCH SITE

EcoSolutions, LLC

ECOSOLDESIGNS . C O M

Lake Champlain

Restoration Technologies

Lake Champlain is plagued by excess nutrients such as nitrogen and phosphorus. These nutrients contribute to harmful algae blooms. Technologies such as Floating Treatment Wetland equipped with Phosphorus Removal & Recovery systems may provide a sustainable solution.

The City of Burlington is partnering with EcoSolutions, LLC, a Vermont based engineering firm specializing in restoration technologies, to trial innovative solutions that will help restore Lake Champlain.

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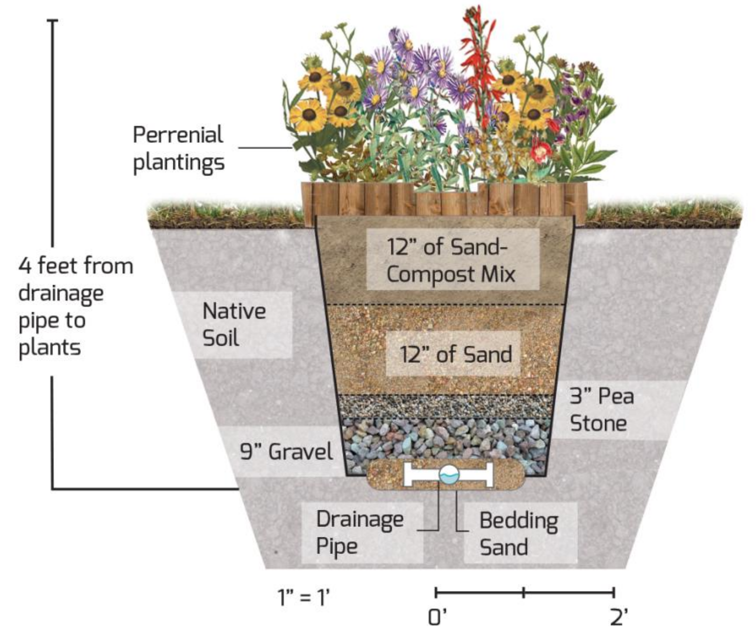
Bioretention
Rain Gardens
Green Streets

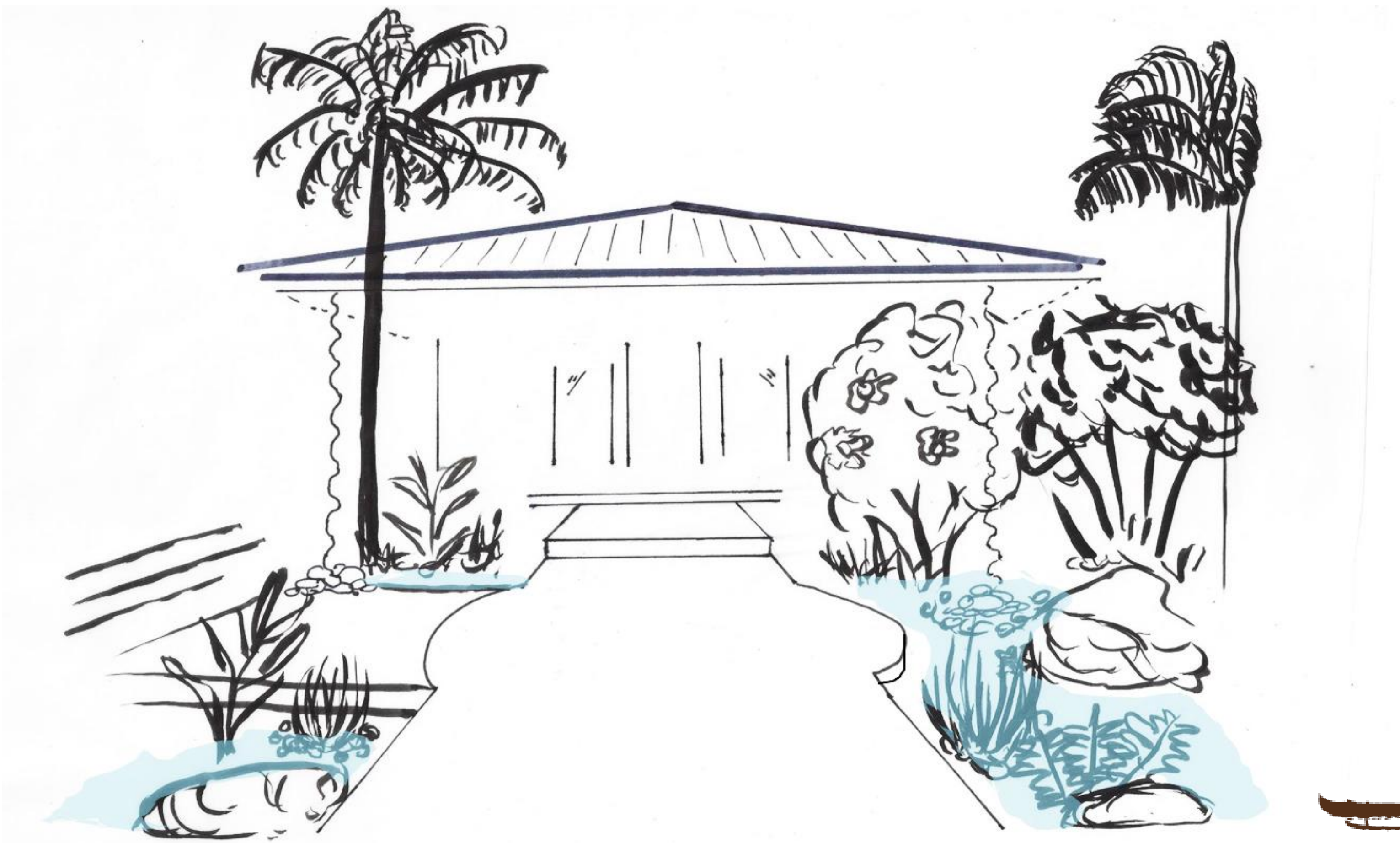
Design Strengths:
Reduces Volume & Peak Flows
Removes Total Suspended Solids
Removes Nutrients
Improved Aesthetics

Design Challenges:
Obtaining proper infiltration
Directing flow into feature
Maintenance

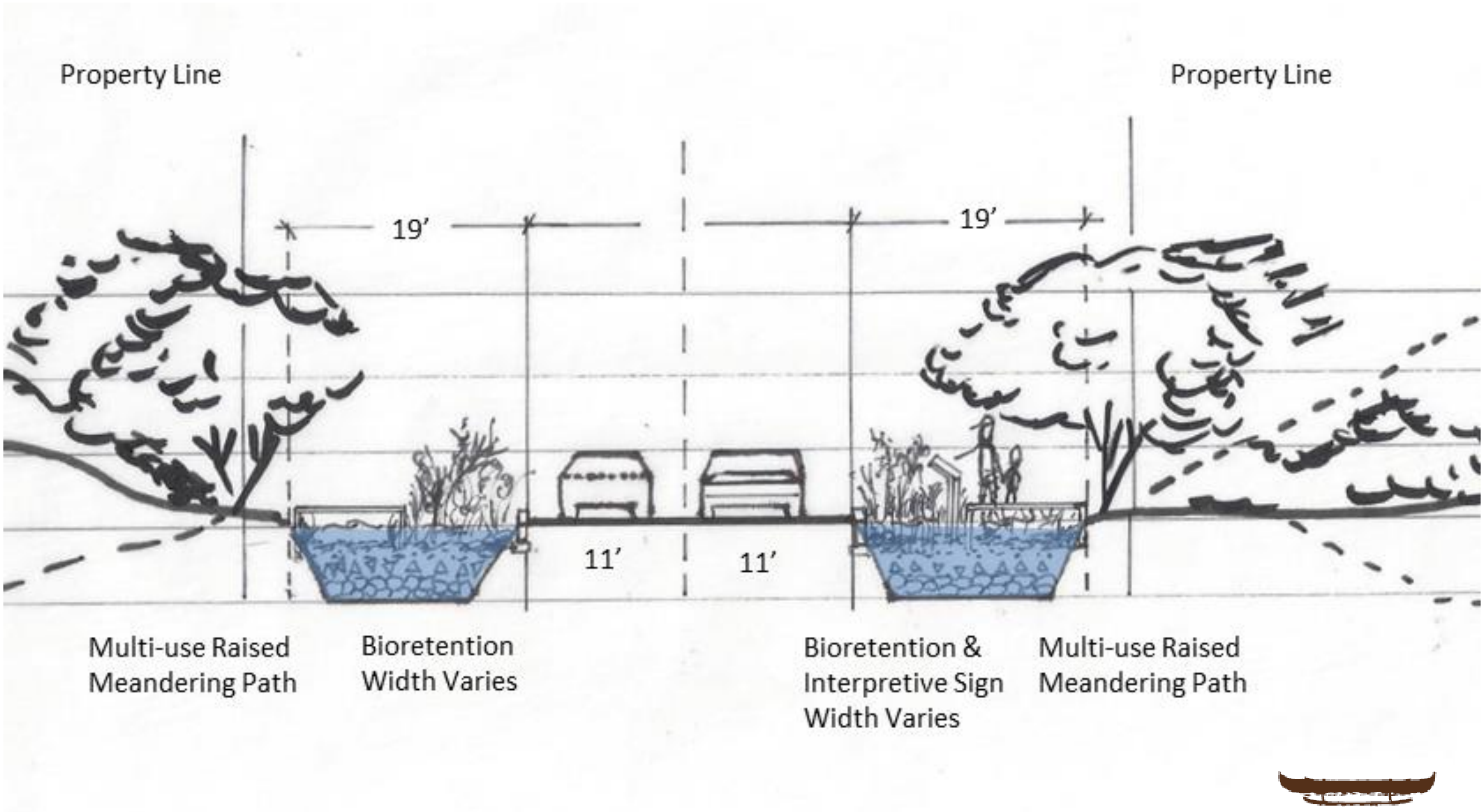





Residential Bioretention



Bioretention Green Streets



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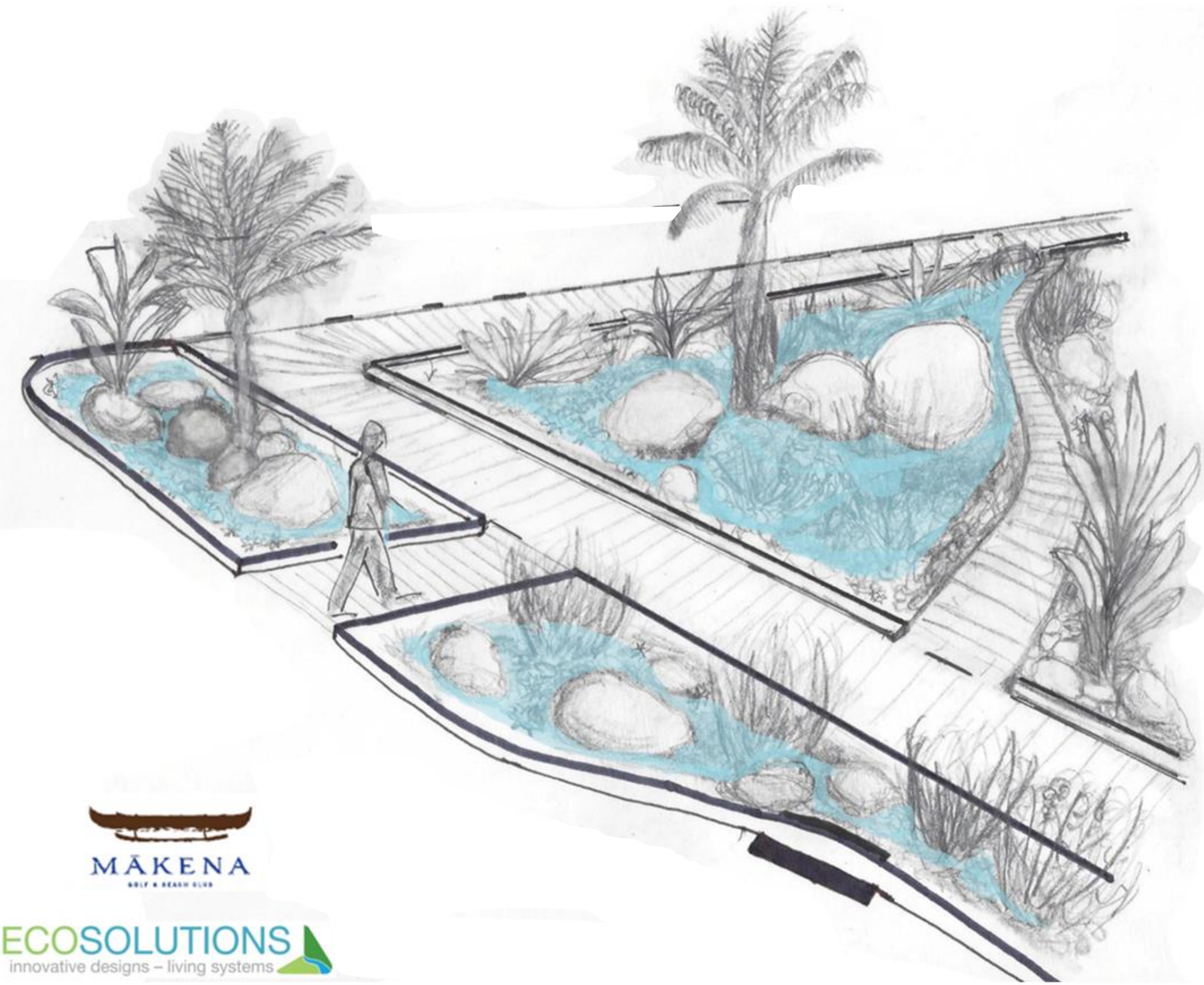
Rendering Produced by Jeff Brink

Bioretention Green Streets



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Neighborhood Scale Bioretention

Commercial Scale Bioretention
NOMA District Washington, DC

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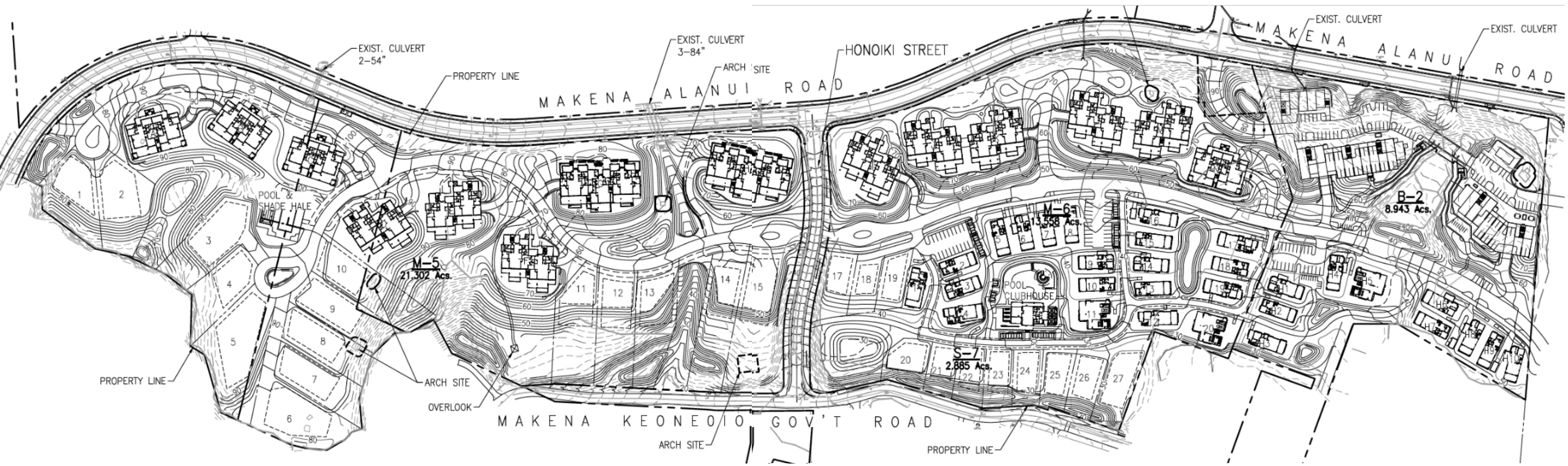
Community Scale LID: Resort Basemap



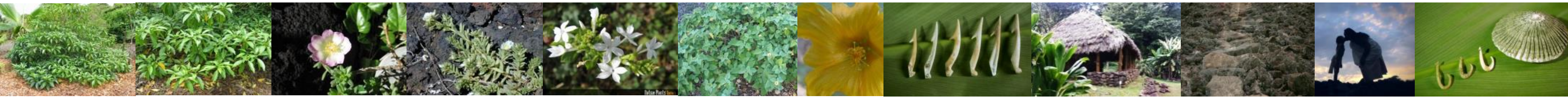
Required to **retain**:

- 100% of the 2.5” (50-yr, 1-hr) storm event

Community Scale LID: Basemap

Bioretention & porous materials can **retain + treat**:

- ➢ 100% of the 2.5” (50-yr, 1-hr) storm event
- ➢ 100% of the 3.0” (100-year, 1-hr) storm event

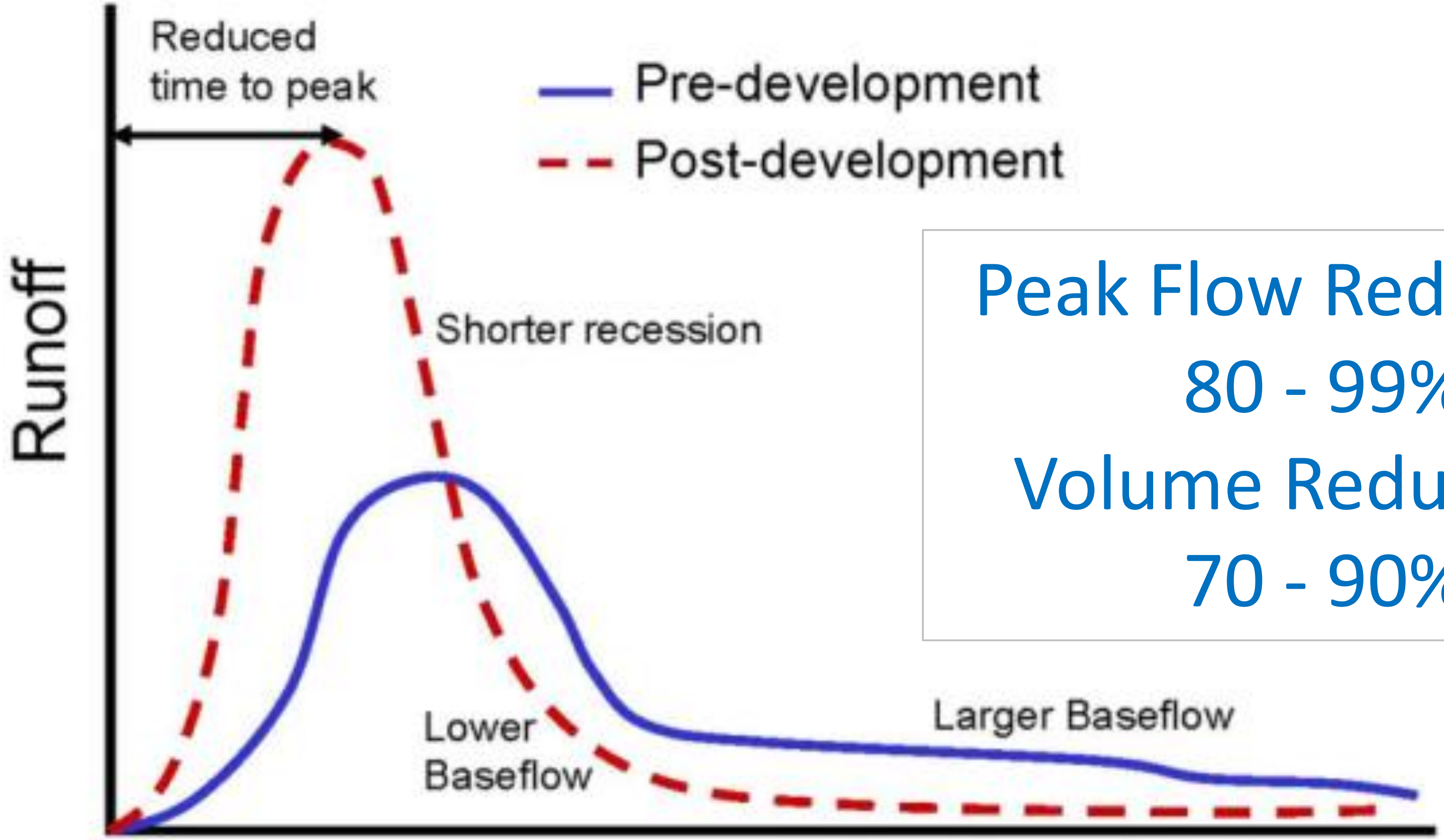


Collect Data to Verify Effectiveness

Pollutants Found in Stormwater:

bacteria
pathogens
cadmium
chromium
copper
lead
mercury
zinc
phosphorus
nitrogen
oil and grease
total suspended solids

Bioretention: Hydrologic Performance

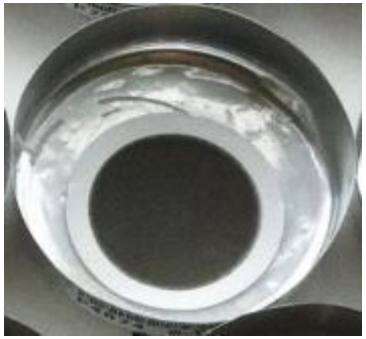


Peak Flow Reduction:
80 - 99%
Volume Reduction:
70 - 90%

Hunt et al. (2008); Debusk et al. (2011); Image Source: Liu et al. (2014)

Bioretention: Sediment Removal

Removal of
Total Suspended Solids:
70% - 99%



Brown and Hunt (2011); Bratieres et al. (2008); Hatt et al. (2008)

Stormwater Pollutant Concentrations

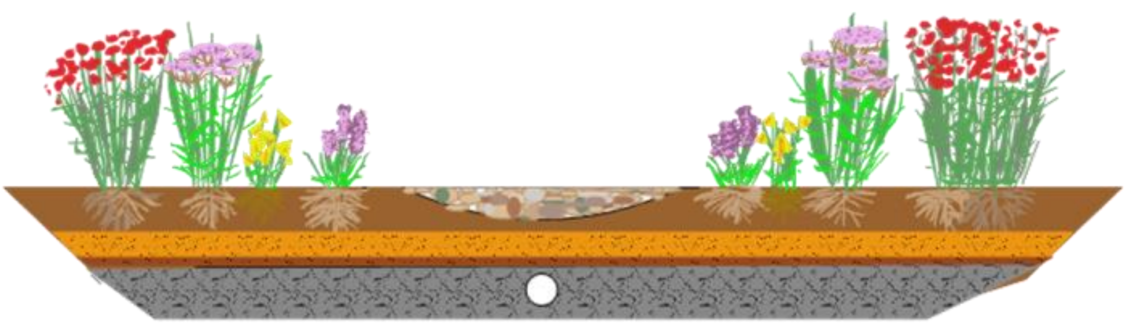
Author	TP	NLP	SRP	TN	TKN	NO_3^-	TSS
	µg L^{-1}	µg L^{-1}	µg L^{-1}	µg L^{-1}	µg L^{-1}	µg L^{-1}	mg L^{-1}
Dietz and Clausen (2005)	19	-	-	1,200	700	500	-
Alias et al. (2014)	74	-	-	1,170	-	-	41
Hunt et al. (2006)	105	52	53	1,310	880	420	-
Geosyntec (2012)	110	100	10	1,250	940	260	38
Bratieres et al. (2008)	427	300	127	2,210	-	790	160
Brezonik and Stadelmann (2002)	580	380	200	3,080	2,620	530	184
Davis (2007)	1,200	-	-	-	-	133	37
Range	**19 – 1,200**	**52 – 380**	**10 - 200**	**940 – 3,080**	**700 – 2,620**	**133 – 790**	**38 - 184**

Total Nitrogen (TN) = Total Keldahl Nitrogen (TKN) + Nitrate (NO_3^-)

Total Phosphorus(TP) = Non-Labile Phosphorus (NLP) + Soluble Reactive Phosphorus (SRP)

Average Bioretention Outflow Concentrations

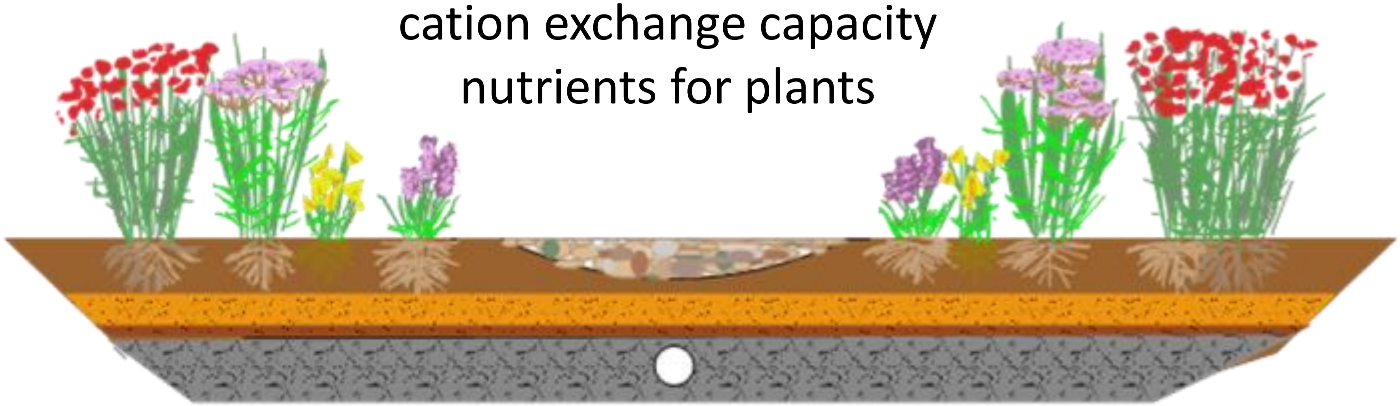
Parameter	Literature	Reference
NLP	40 – 800 µg L^{-1}	Hunt et al. (2006)
SRP	210 – 670 µg L^{-1}	Geosyntec (2008)
SRP	140 µg L^{-1}	Chardon et al. (2005) (Iron Coated Sand)
	< 10 µg L^{-1}	O'Neill and Davis (2011) (WWT Residual)
NO_3^-	300 – 400 µg L^{-1}	Dietz and Clausen (2006)
TKN	1,240 – 1,780 µg L^{-1}	Geosyntec (2008)
TSS	15 – 33 mg L^{-1}	Geosyntec (2008)



Inconsistent Nutrient Removal

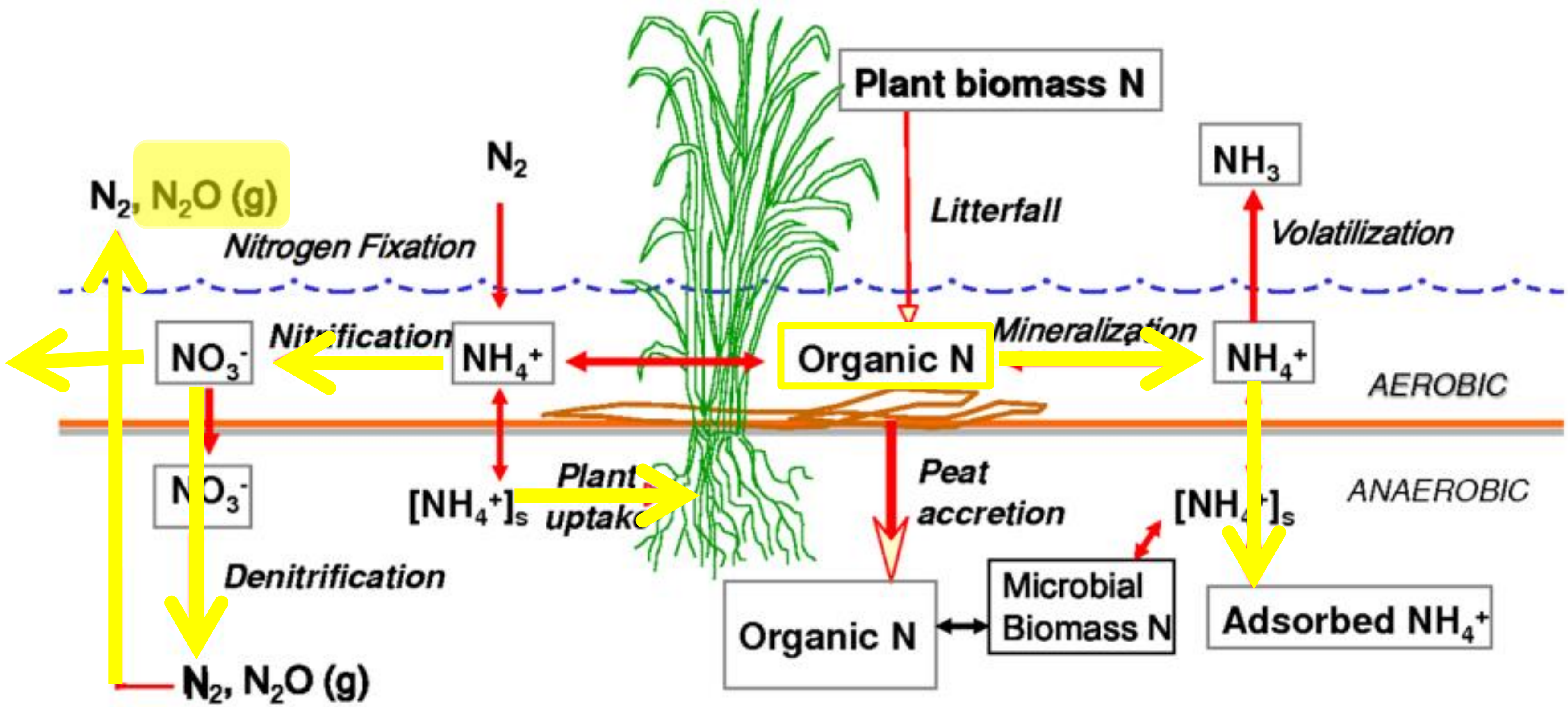
- Some of the variability could be attributed to <u>soil media selected</u>
- Sand based bioretention soil designs are common
- Organic amendments (<u>compost</u>, mulch) are recommended for:

metals removal
soil moisture retention
cation exchange capacity
nutrients for plants



Bratieres et al. 2008; DeBusk and Wynn 2011; Michigan Department of Environmental Quality 2008; Thompson et al. 2008; Vermont Agency of Natural Resources 2002; Washington State University Pierce County Extension 2012.

Nitrogen Removal Mechanisms



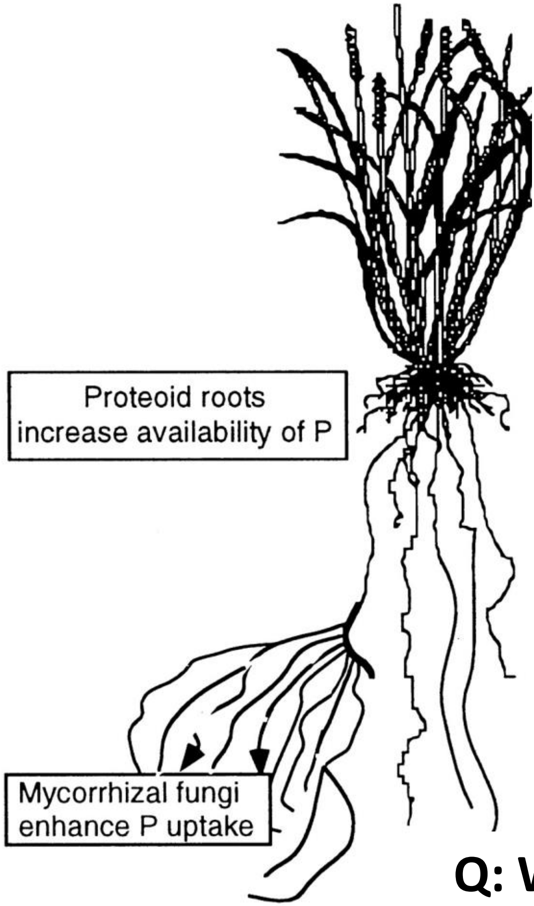
***Mn (II) may also reduce NO_3^- via chemo-denitrification**

Q: Which mechanisms are dominant in bioretention?

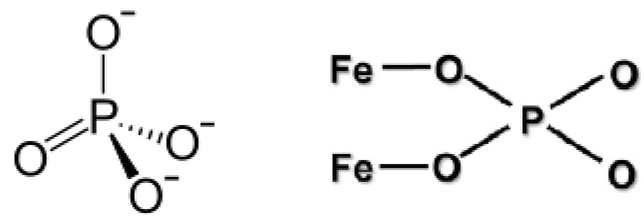
Q: How can we maximize removal through design?

Davis et al. (2006); Bratieres et al. (2008); Kim et al. (2003); Charpuis-Lardy et al. (2007)

Phosphorus Removal Mechanisms



1. Physical Filtration: Non-labile P (NLP)
2. Sorption of SRP: Fe, Ca, and Al in Soil



$$2{\equiv}FeOH^{-0.5} + PO_4^{3-} + 2H^{+} = ({\equiv}FeO)_2PO_2^{2-} + 2H_2O$$

3. Plant Uptake: SRP

Q: Which mechanisms are dominant in bioretention?

Q: How can we maximize removal mechanisms through design?

Tanner (1996); Arias et al. (2001); Lucas and Greenway (2011); Liping et al. (2012)

Soil Media Designed to Remove P

Reference	Media	Composition	Ca	Fe	Al	SRP	TP Removal (%)
Liu et al. (2014)	TerraSolve	15% coir/peat mix, 9% hardwood mulch, 12% WTR, 58% sand	-	1,979	7,541	196	90– 99
	Virginia Institute of Technology Mixture	3% WTR, 15% saprolite, 25% compost, 57% sand	-	6,613	3,367	138	58 – 95
Stoner et al. (2012)	Industrial byproducts	Geothite, gypsum, calcite, quartz, portlandite	90 – 6,500	600 – 40,000	60 – 58,000	-	10 – 60
Arias et al. (2001)	Denmark Sands	Quartz sand	600	1,210	320	40	-
Chardon et al. (2005)	Iron-coated Sand	Iron-coated sand	6,100	198,000	620	3,400	94

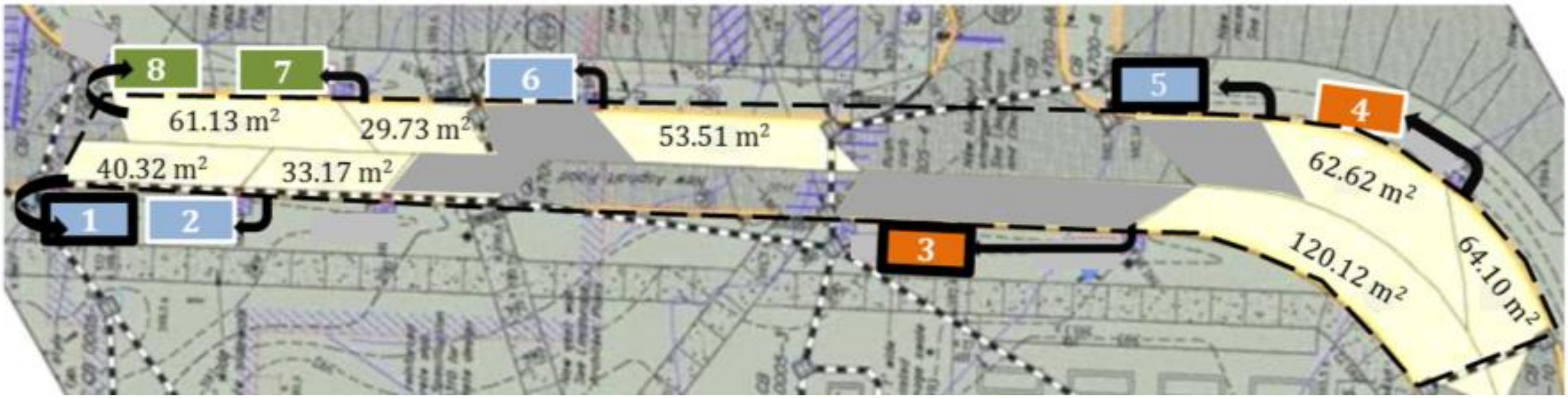
* All constituents are in mg kg^{-1}

Welcome to the University of Vermont Bioretention Laboratory

University of Vermont Bioretention Laboratory

- Constructed by EcoSolutions in November of 2012
- Eight small paved road sub-watersheds
- Total area: 5,000 ft^2 or 0.1 acres
- Drainage Areas: 29.73 m^2 to 120.12 m^2

The Research Site



Research Objectives:

1. How does one monitor bioretention effectiveness?
2. What design parameters dominate pollutant removal?

Step 1: Monitoring Bioretention

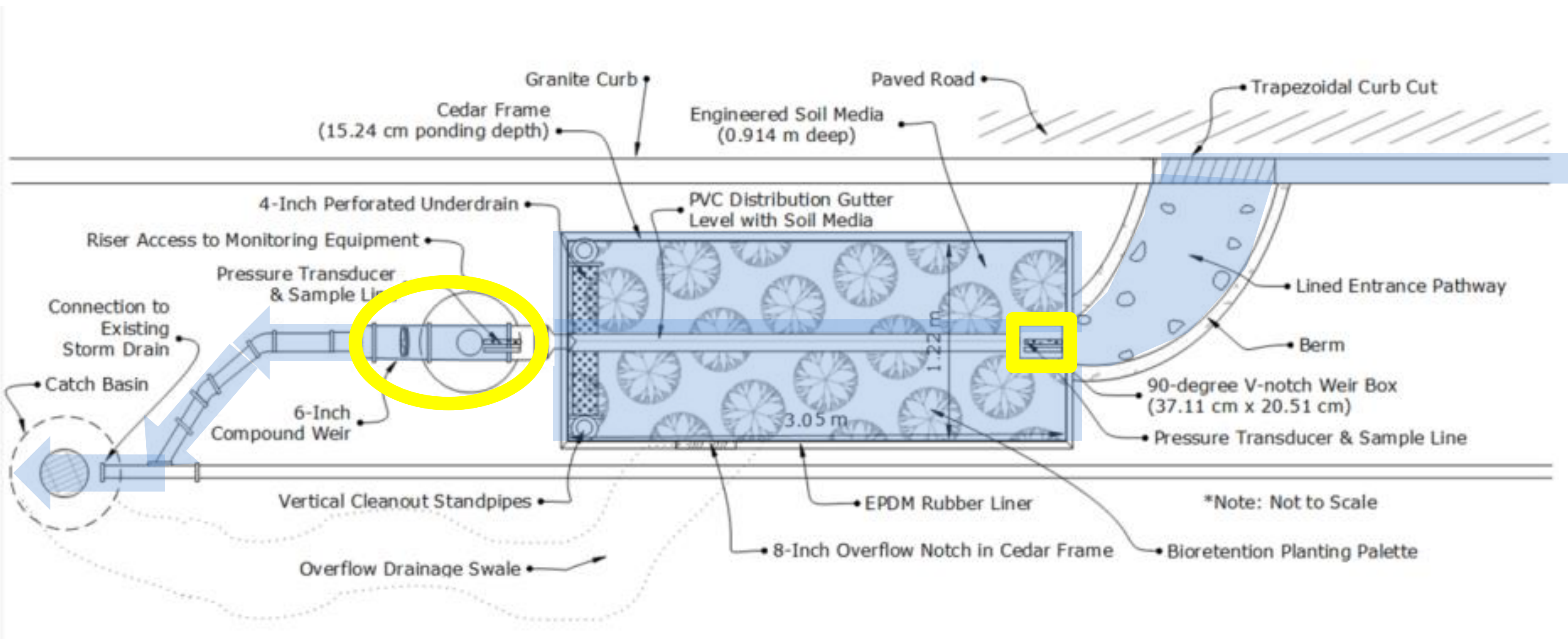
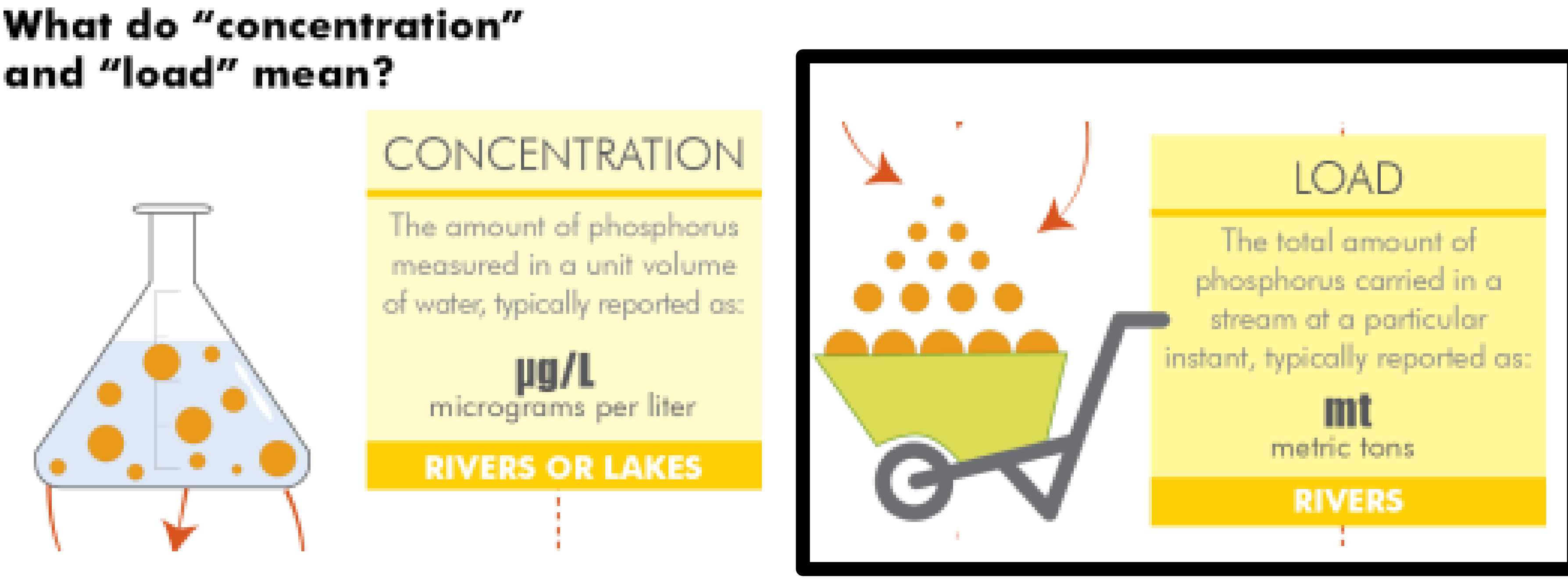


Image Credit: Amanda Cording

What Units Do I Want?
Pollutant Concentration Vs. Mass Load



***Need to Measure Load to Assess Impaired Waters on 303(d) list**


Large Volume = Low Concentration
Yet Potentially Large Pollutant Mass
Load Delivered Downstream

Converting Concentration to Mass with Numeric Integration

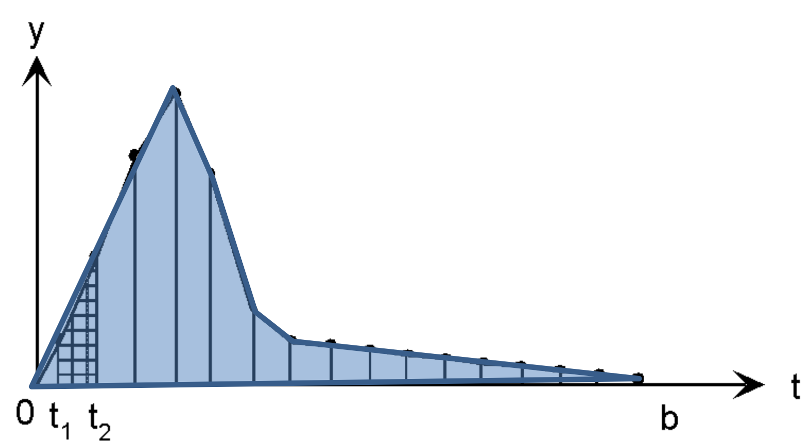
$$V = \int_{t0}^{tn} Q(t)\, dt$$

Where,
V = volume delivered during storm event (L)
Q = flow rate as a function of time (Ls^{-1})

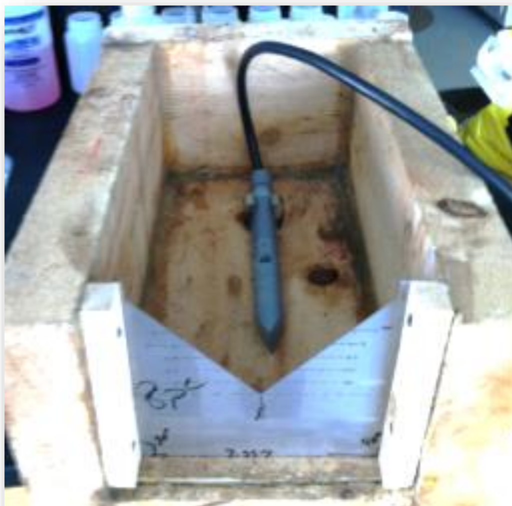
$$M = \int_{t0}^{tn} C(t)dt\; Q(t)\, dt$$

Where,
M = mass delivered during storm event (µg or mg)
C = concentration as a function of time (µg L^{-1})
Q = flow rate as a function of time (Ls^{-1})

$$Area = (t_2 - t_1)\left[\frac{f(t_1) + f(t_2)}{2}\right]$$



How do you measure flow rate entering and exiting bioretention?



Inflow 90º Weir Box

Outflow Thel-Mar™ Weir

$$Q=CH^n$$

Where:

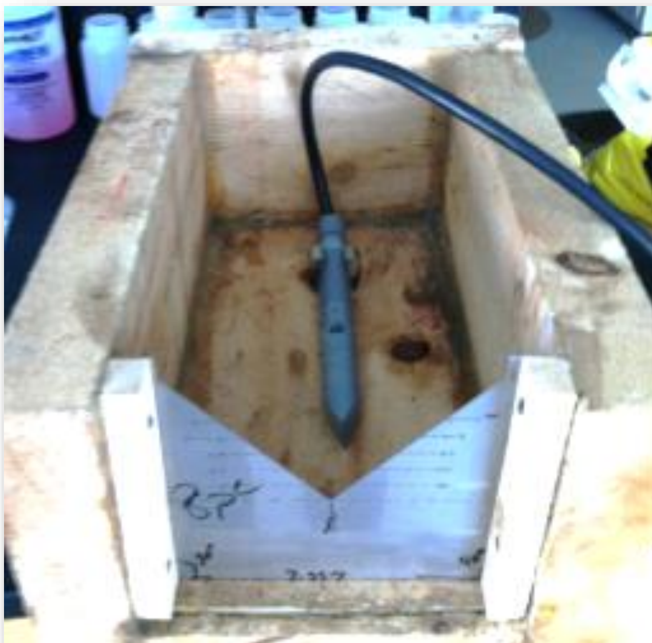
Q = flow rate over the weir (cfs, L s^{-1})

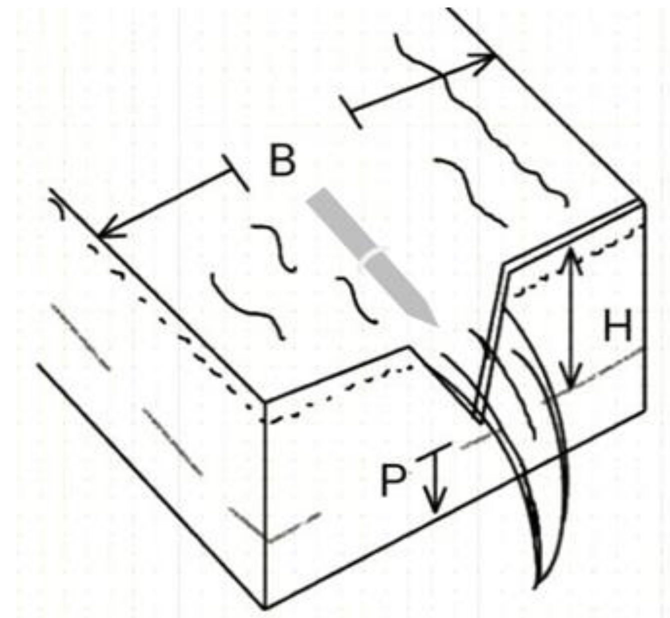
C= coefficient of discharge, or weir coefficient

H= height of water behind the weir (pressure transducer)

n = an empirical exponent (dimensionless)

Measuring Road Runoff



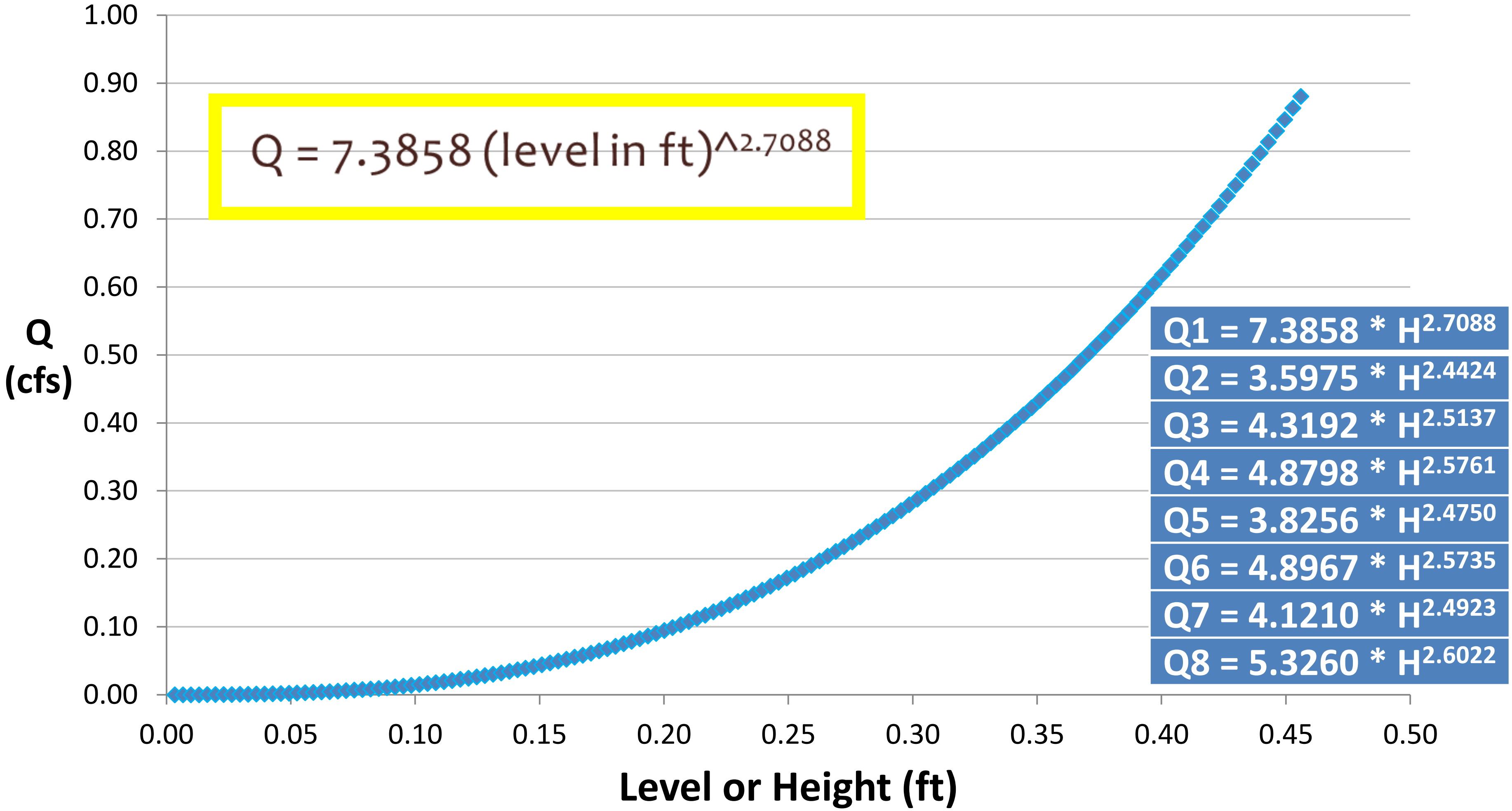


Weir thickness = 1.59 mm stainless steel
Teledyne™ ISCO Model 720 Pressure Transducer

Maximum Capacity = 10.05 L

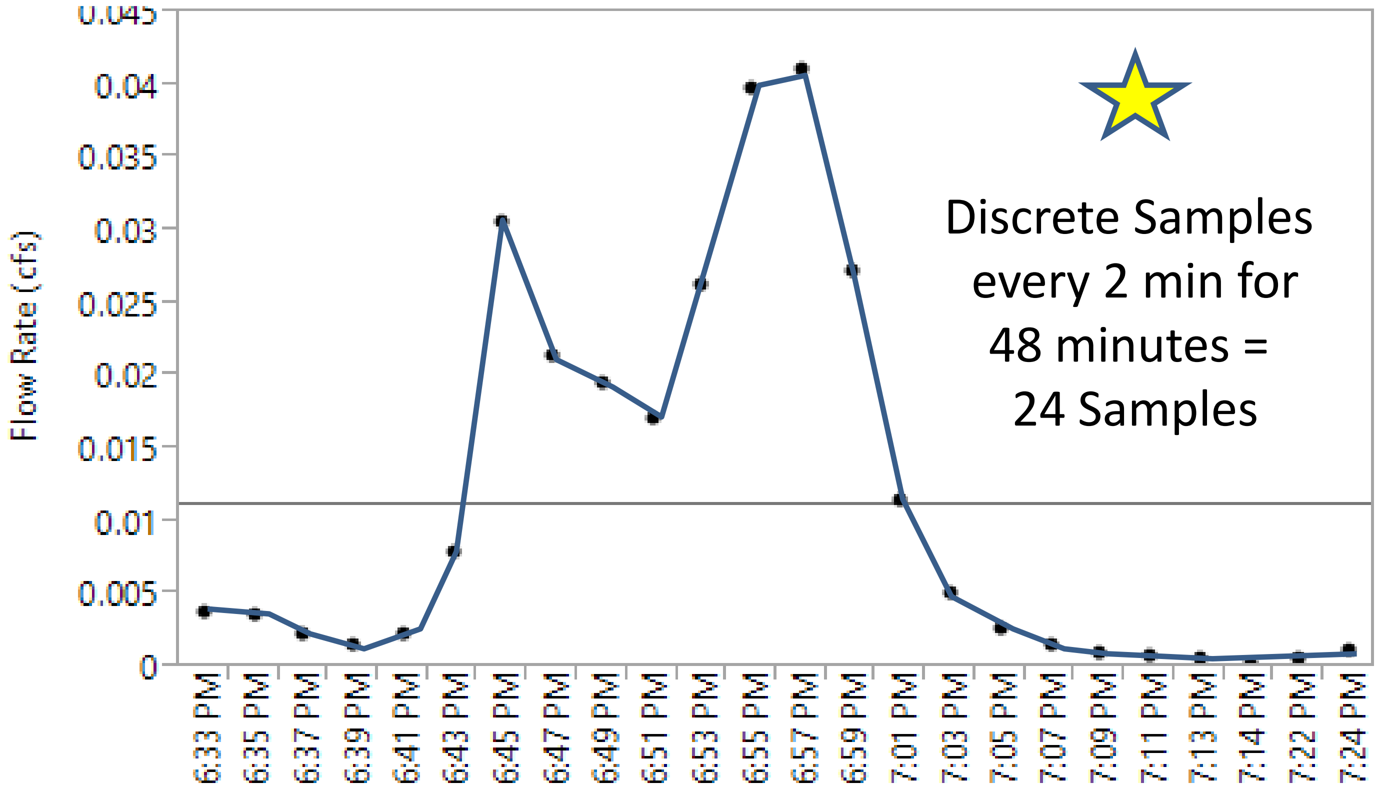
ASTM – D5242; U.S. Bureau of Reclamation (2001)

Developing a Weir Rating Curve

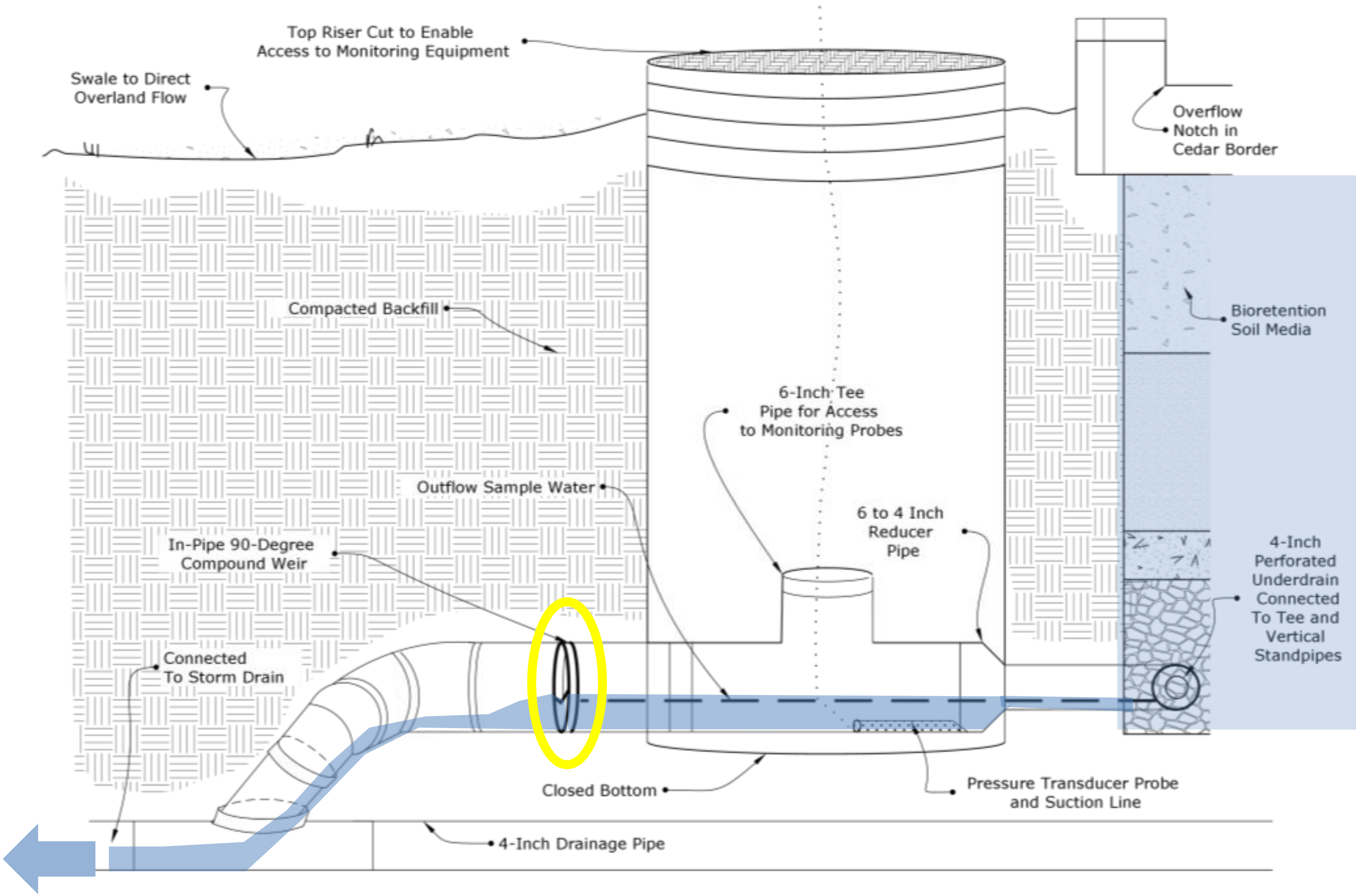


Take Multiple Samples within the Inflow Hydrograph

$$Time = \frac{watershed\ area\ x\ rainfall\ depth}{peak\ flow\ rate}$$



Outflow Monitoring: In-Pipe Thel-Mar™ Weir



Capturing the Outflow Hydrograph: Estimate Hydraulic Conductivity

$$K_z = \frac{D}{\sum_{i=1}^{n} \frac{d_i}{k_i}}$$

Where,

K_z is the vertical hydraulic conductivity for the layered system (m s^{-1})

D is the total cumulative depth of the layers (m)

d_i is the depth of a given layer (m)

k_i is the hydraulic conductivity of a given layer (m s^{-1})

$$K_x = \sum_{i=1}^{n} \frac{K_i d_i}{d}$$

Where,

K_x is the horizontal hydraulic conductivity (m s^{-1})

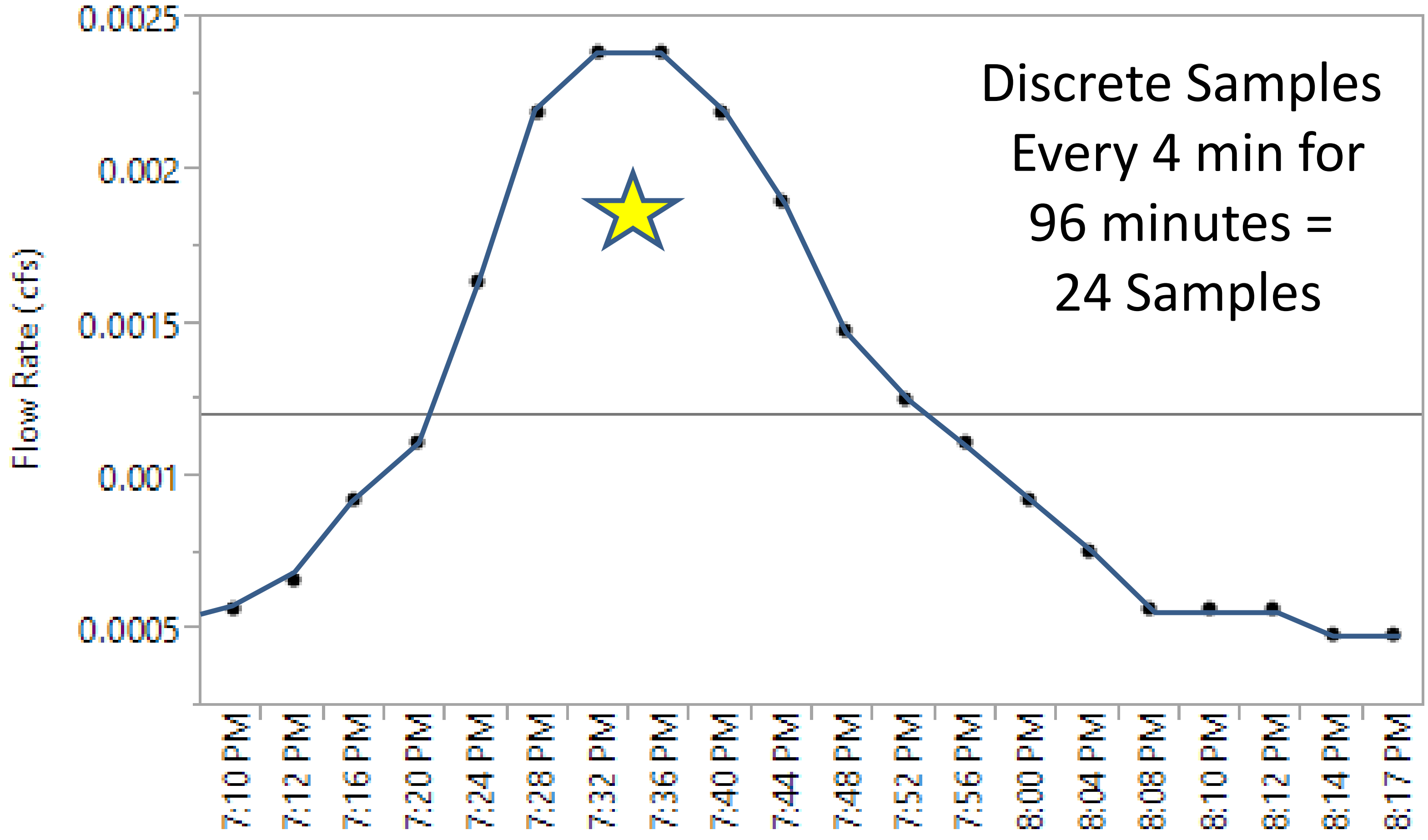
d_i is the depth of a given layer (m)

K_i is the hydraulic conductivity of a given layer (m s^{-1})

d is the horizontal distance of the given layer (m)

Sampling the Outflow Hydrograph

Time Needed to Monitor Outflow Hydrograph = 90 minutes



Installing Outflow Monitoring Equipment

Photo Credit: Amanda Cording, Paliza Shrestha

Numerous Design Factors that Affect Pollutant Removal Performance

Factor	Authors
1. Residence time	(Collins et al. 2010; Hurley and Forman 2011; Kadlec et al. 2010; Rosenquist et al. 2010)
2. Media depth	(Brown and Hunt 2011)
3. Vegetation type, root depth, root architecture	(Claassen and Young 2010; Collins et al. 2010; Davis et al. 2009; Kadlec et al. 2010; Lucas and Greenway 2008)
4. Soil organic matter content, use of mulch	(DeBusk and Wynn 2011; Fassman et al. 2013)
5. % sand, silt, and clay	(Liu et al. 2014)
6. Chemical characteristics of soil media (Fe, Ca, Al)	(Groenenberg et al. 2013; Vance et al. 2003)
7. Ponding depth, hydraulic conductivity, infiltration rate	(Thompson et al. 2008)
8. Inclusion of internal water storage (IWS) zones	(Chen et al. 2013; Dietz and Clausen 2006; Hunt et al. 2006)
9. Careful construction, maintenance	(Brown and Hunt 2011; Dietz and Clausen 2006)

Step 2: Testing Bioretention Designs

1. Vegetation: Plant Palette 1 vs. Plant Palette 2


2. Soil Media: Conventional vs. Sorbtive Media™


Methods: Measuring Stormwater Quality

Equipment	Parameter	Sampling and Analysis Methods
6700 Series Automatic Samplers (Teledyne™) Model 720 Differential Pressure Transducer	1. TP 2. NLP 3. SRP 4. TN 5. TKN 6. NO_3^- 7. TSS 8. Flow Rate	• Time Based • Discrete Samples • Based on the Hydrograph • Inflow = Every 2 min for 48 min (950 mL) • Outflow = Every 4 min for 96 min (500 mL) • Inflow to Outflow, 20-L increments (n = 6) • Outflow to Outflow, 20-L increments (n = 6) • Partial Event Mean Concentration (PEMC)



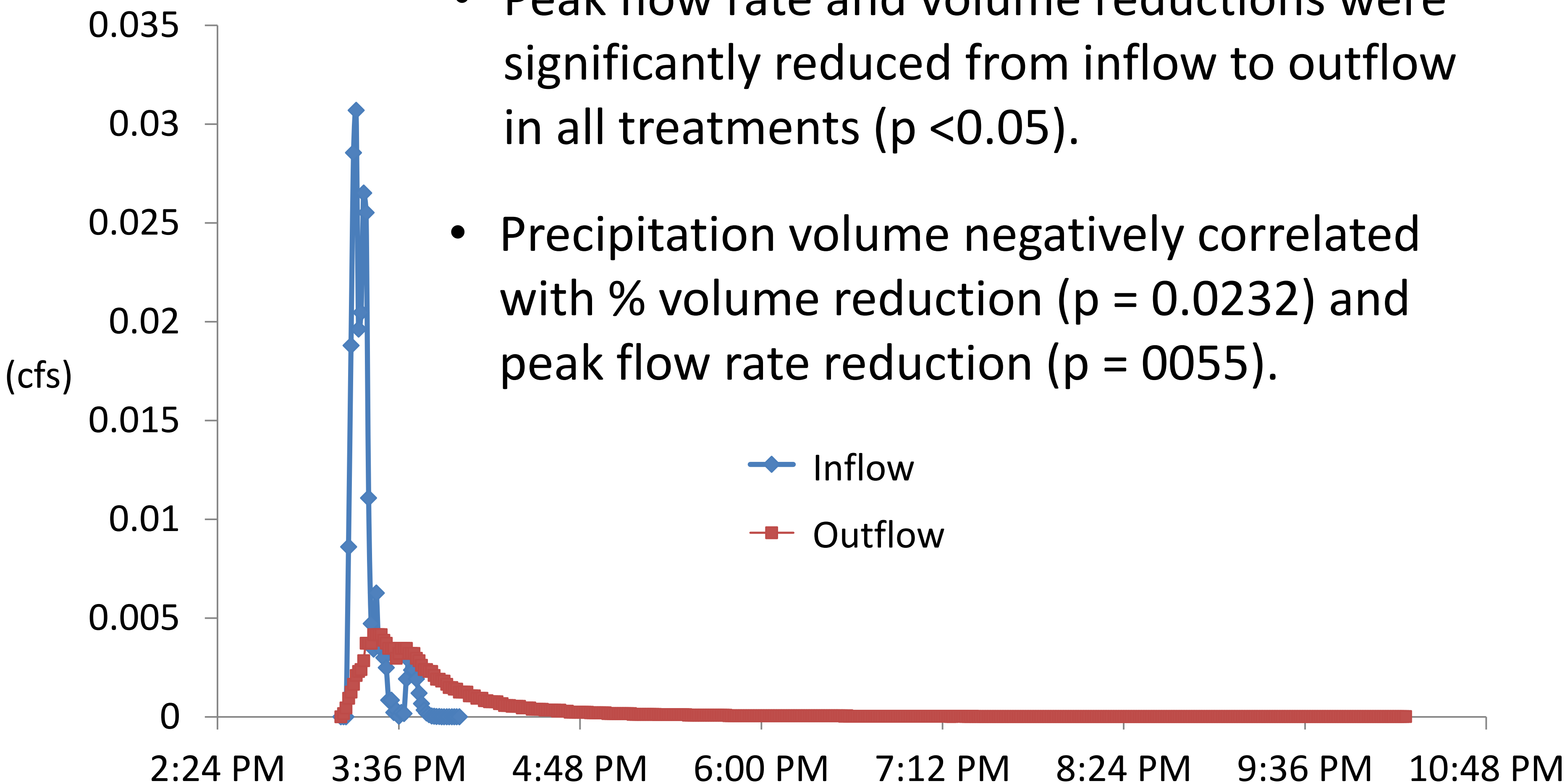

Methods: Measuring Bioretention Soil Media Characteristics

Equipment	Parameter	Sampling Method
Soil auger Soil core cylinder Trowel Decagon soil probes	1. NH_4^+ (n = 13) and NO_3^- (n = 13) 2. SRP (n = 7) 3. Bulk Density (n = 11) 4. Ca, K, Mg, Na, S, Mn, Al, Fe, Zn, Cu (n = 7) 5. Cation exchange capacity (CEC) 6. Organic matter content (n = 7) 7. Volumetric water content 8. Electrical conductivity 9. Soil temperature	1. 2 M KCl extraction 2. Modified Morgan 3. Change in mass /volume 4. Inductively coupled plasma spectroscopy 5. Ammonium acetate 6. Loss on ignition (375°C) 7. Soil probe (Every 5 min) **3 composited sub-samples per bioretention cell**

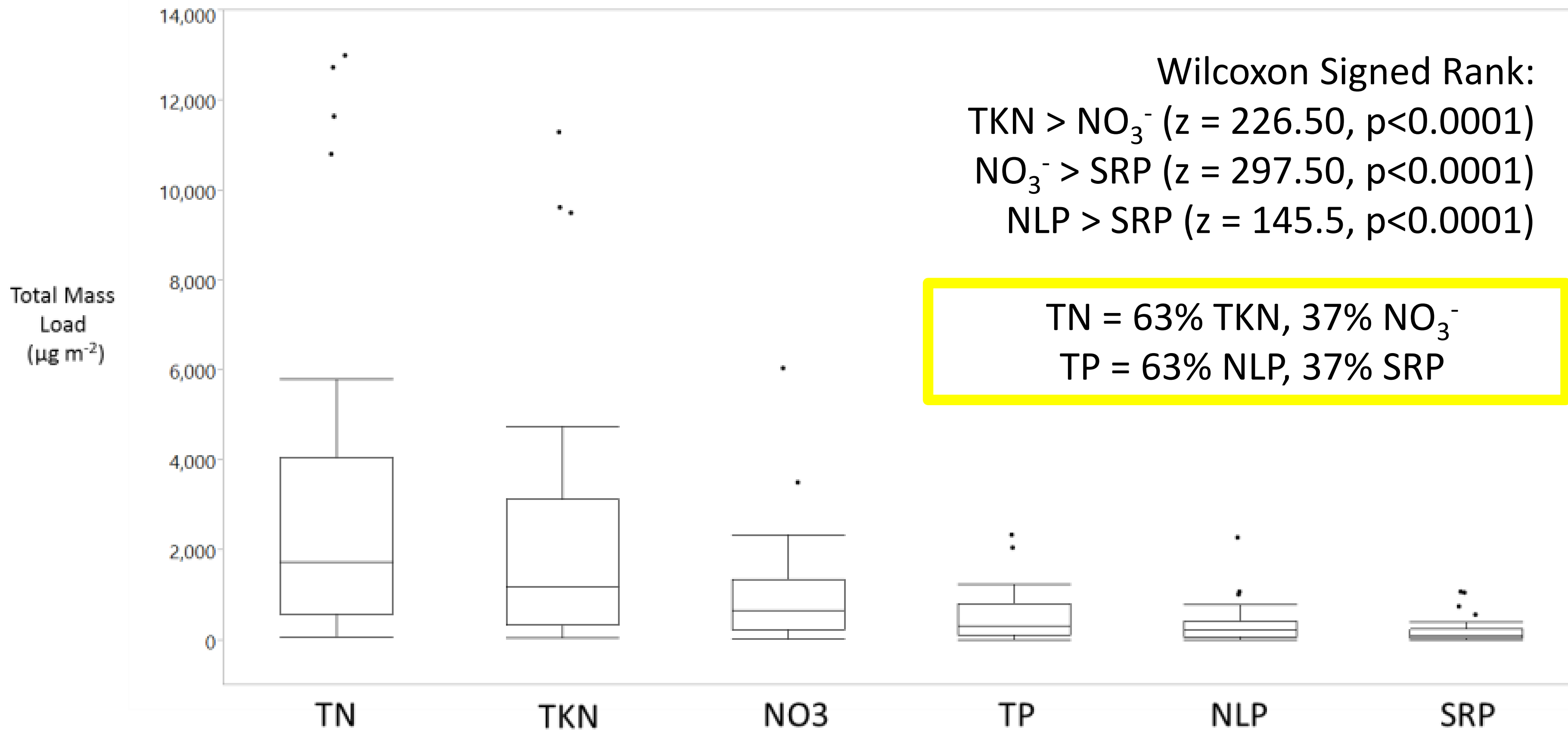



Hydrologic Performance Results

- Peak flow rate and volume reductions were significantly reduced from inflow to outflow in all treatments ($p < 0.05$).
- Precipitation volume negatively correlated with % volume reduction ($p = 0.0232$) and peak flow rate reduction ($p = 0055$).

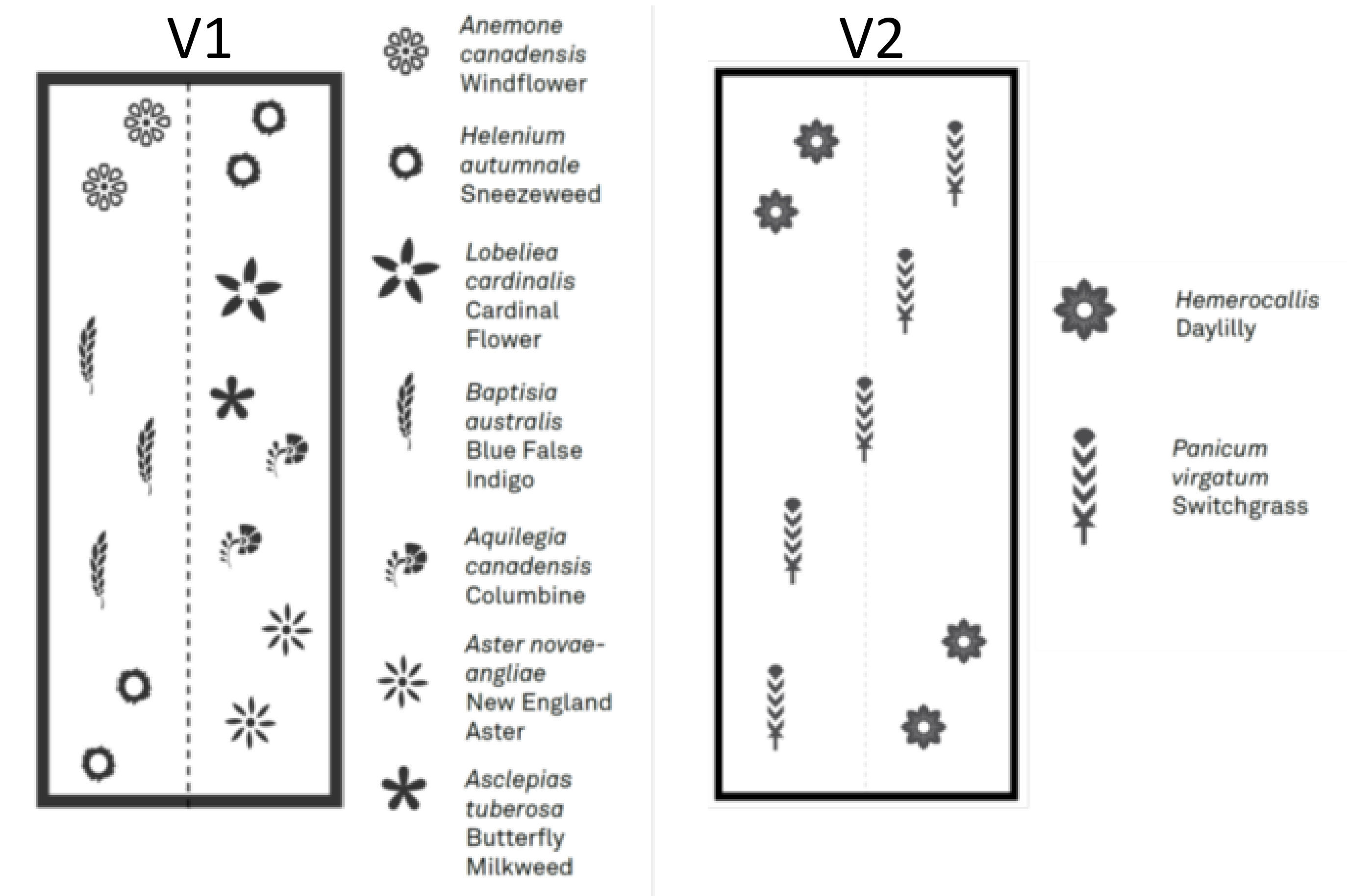


Relative Dominance of N and P Constituents in Stormwater



Box plot of cumulative stormwater mass load delivered across all watershed event (n = 35) for each nutrient constituent.

Comparing Vegetation Treatments



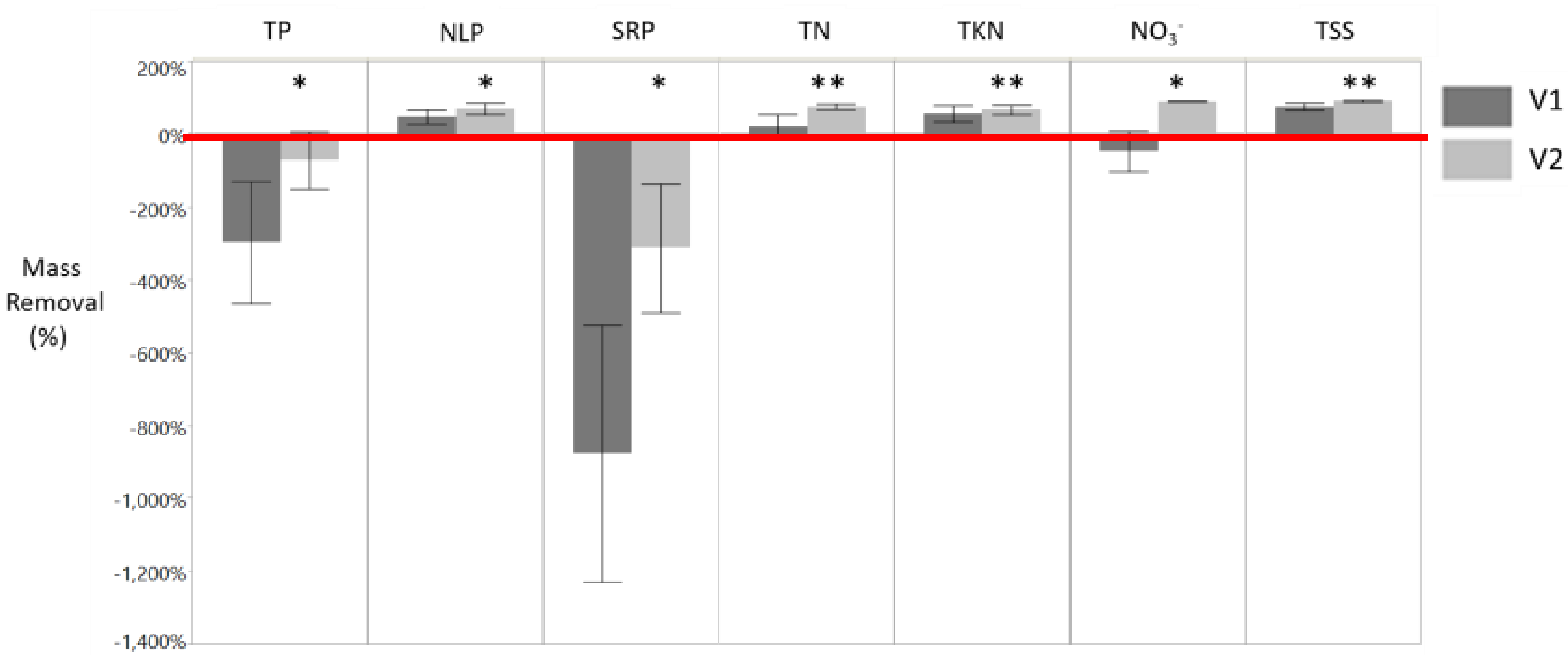
Vegetation Palette 1 (left) and Vegetation Palette 2 (right)

(Diagram created by S. Hurley and A. Zeitz, unpublished).

Vegetation 1 (V1)

Vegetation 2 (V2)

Comparing Vegetation Treatments



ns = p > 0.05, * = p ≤ 0.05, ** = p ≤ 0.01, *** = p ≤ 0.001, **** = p ≤ 0.0001.

Paired t-test (n = 6) results indicate that V2 retained a higher pollutant mass load than V1 for all constituents

Discussion: Differences Between Treatments

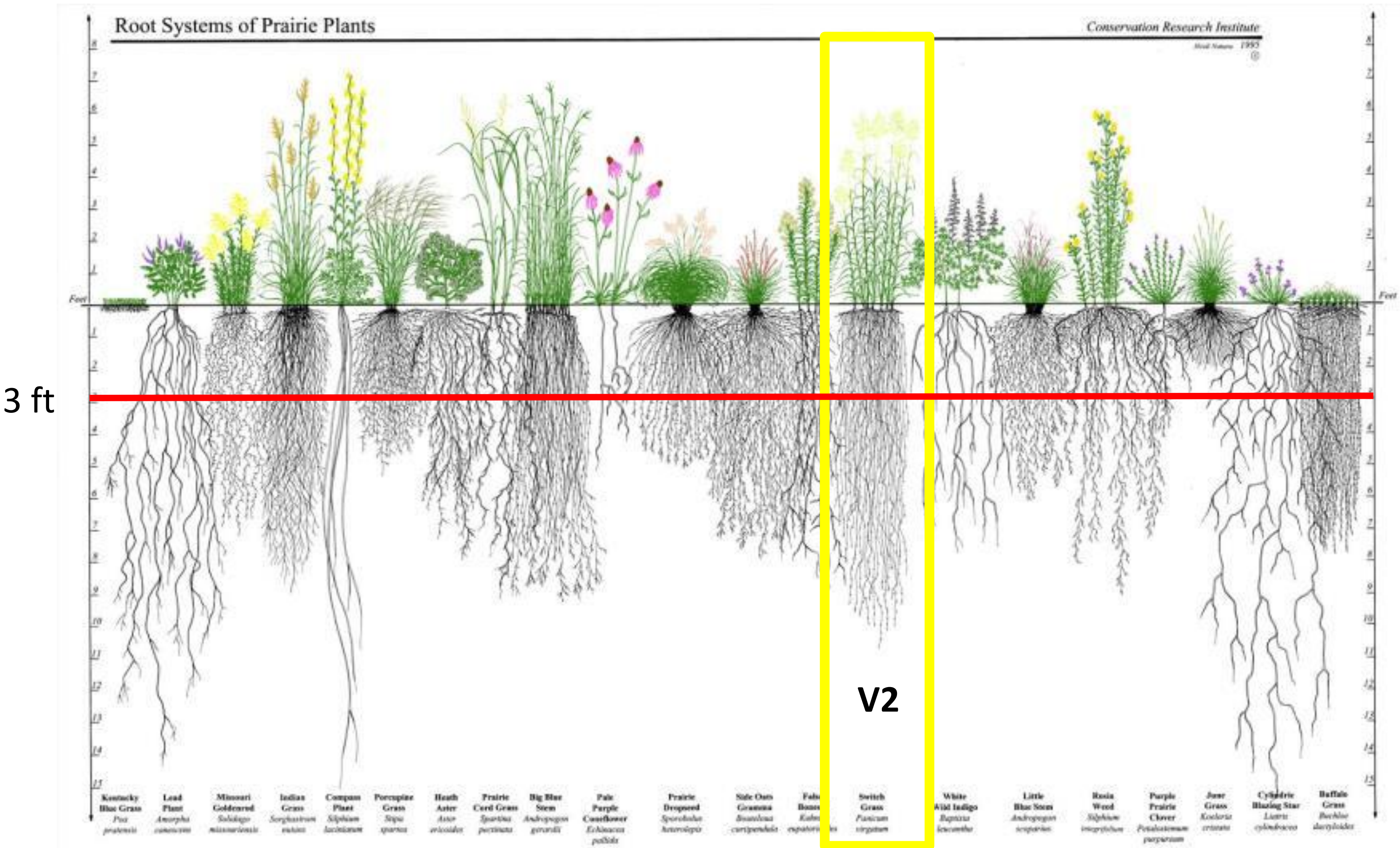
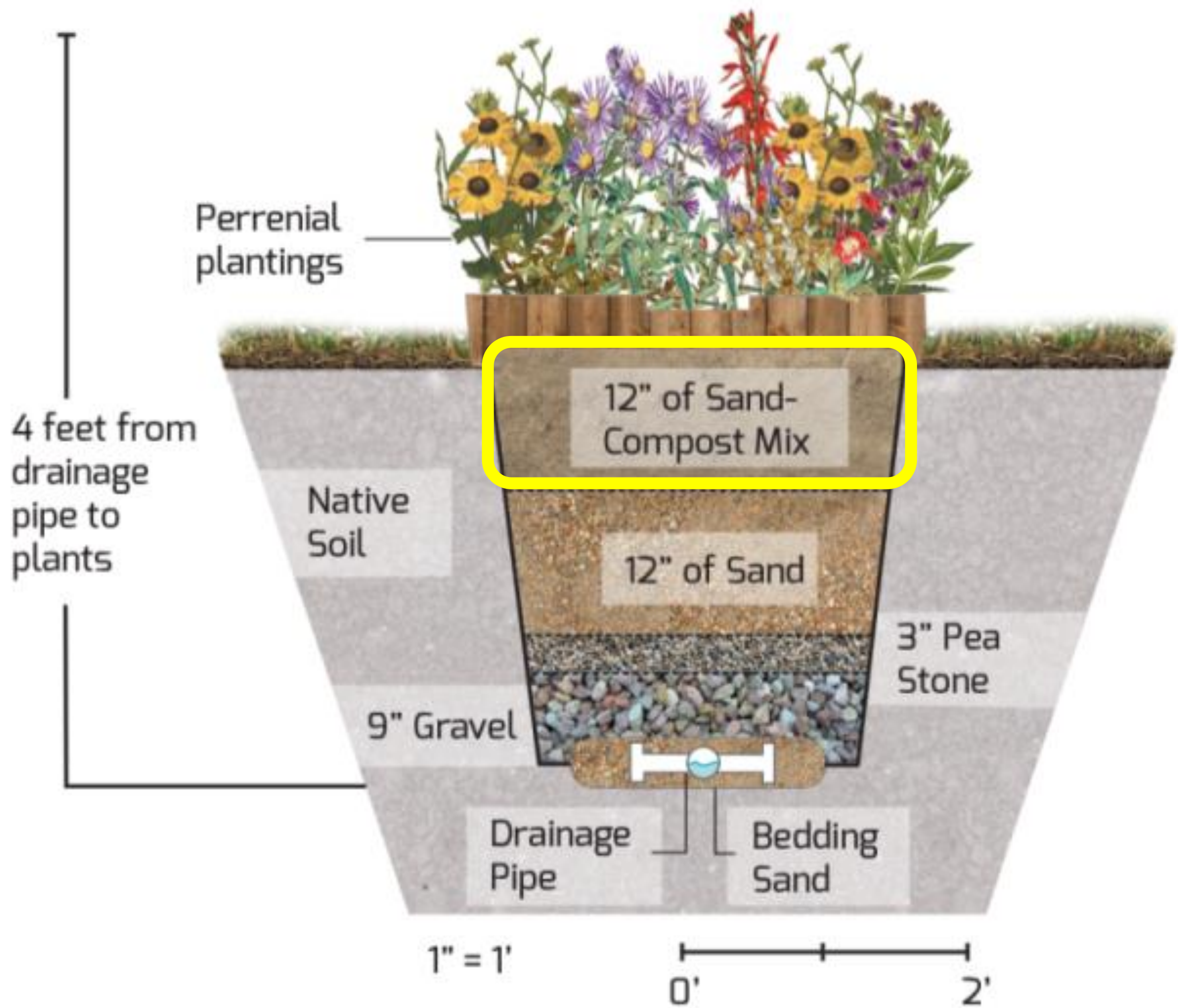


Image Source: Conservation Research Institute; Mann et al. (2013)

Conventional Bioretention Media Design



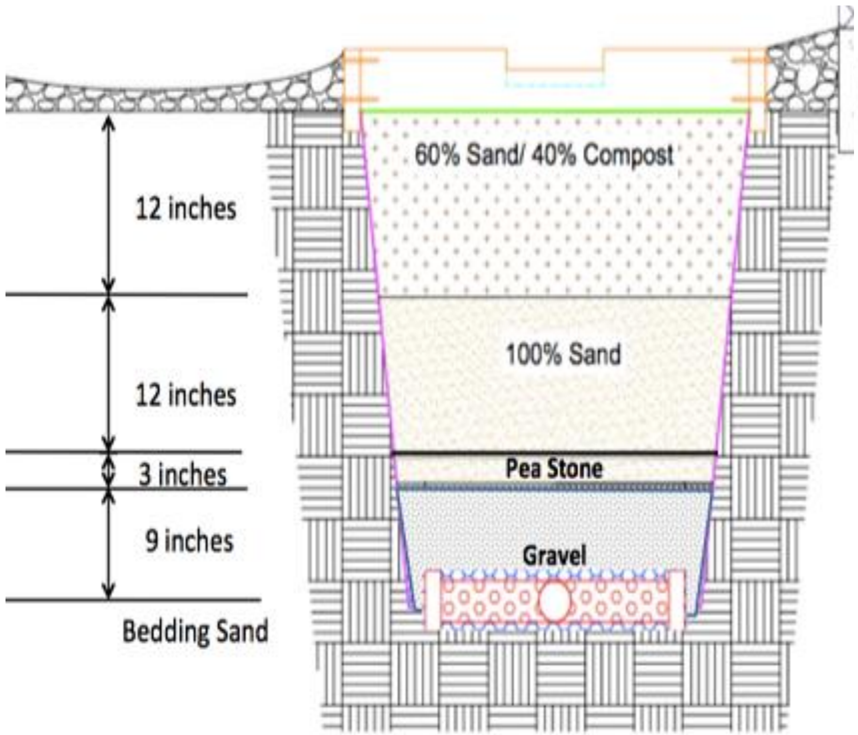
<u>Recommended By:</u>

1. Vermont Agency of Natural Resources (2002)
2. Washington State University Pierce County Extension (2012)
3. Center for Watershed Protection

Image Credit: Hurley, S., Zeitz, G.,(unpublished)

Comparing Soil Media Treatments

Conventional Media (CM)



Sorbtive Media ™ (SM)

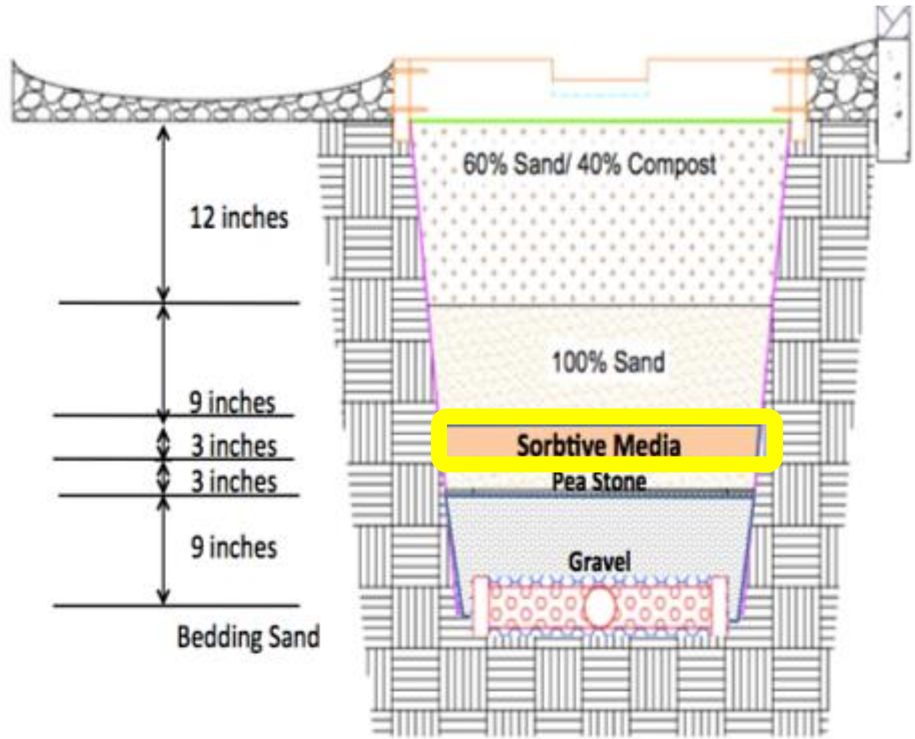


Image Credit: J. Schultz, C. Brackett, J. Nummy, O. Lapierre (unpublished).

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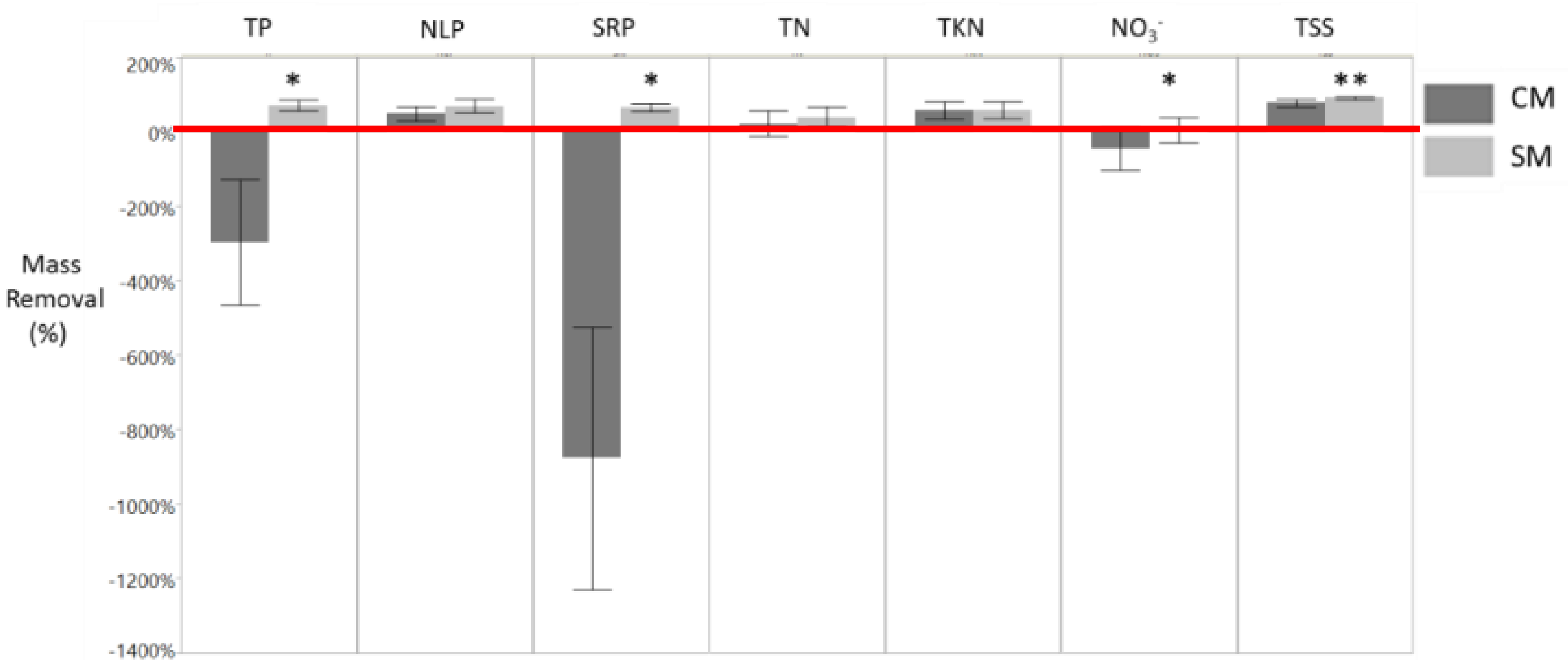
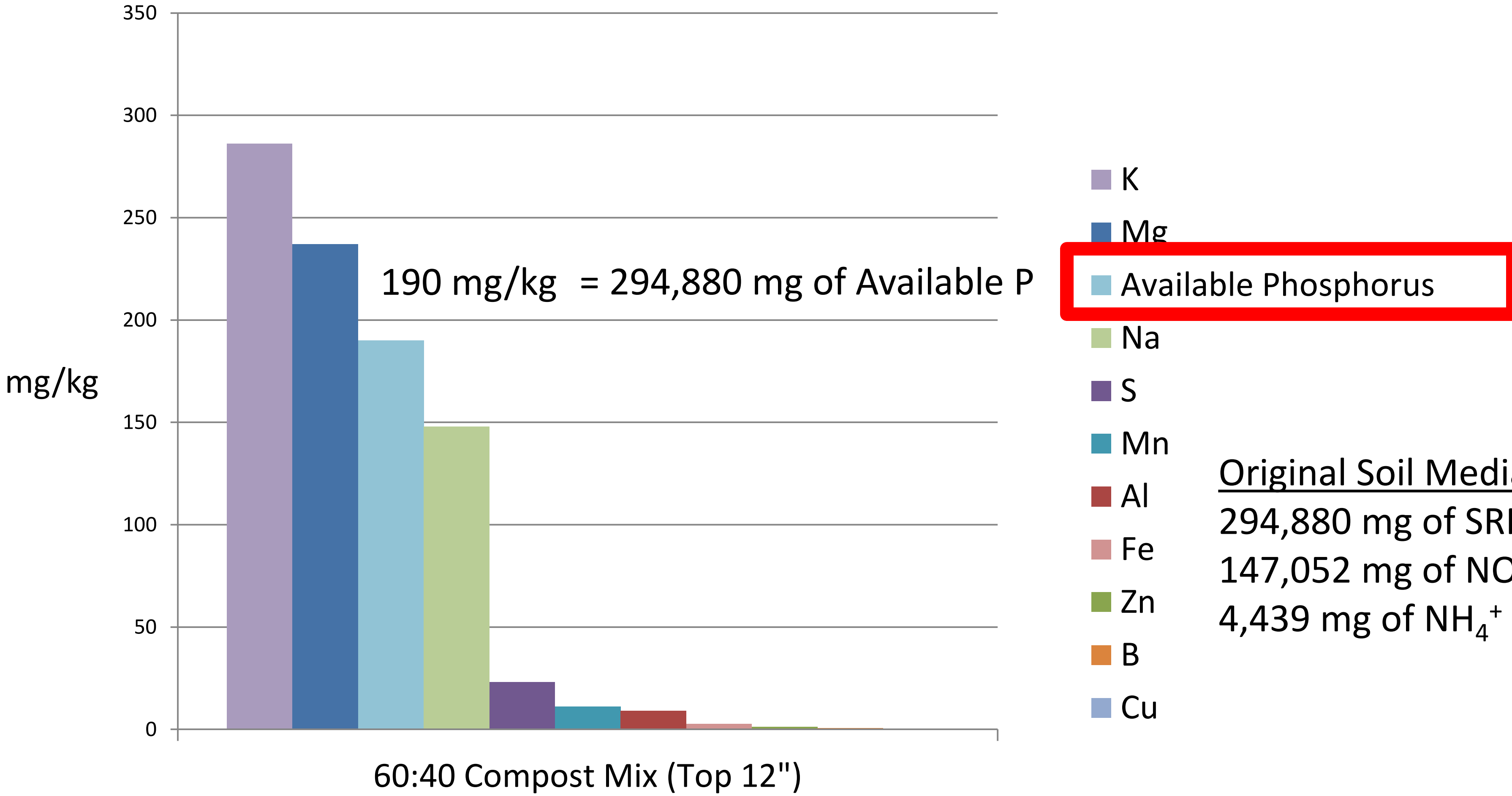
Comparing Soil Media Treatments



ns = p > 0.05, * = p ≤ 0.05, ** = p ≤ 0.01, *** = p ≤ 0.001, **** = p ≤ 0.0001.

1. Sorbtive Media (SM) retained more pollutant mass than Conventional Media (CM) for all constituents except NLP and TKN.
2. Conventional Media (CM) exported SRP and NO_3^-

Conventional Bioretention Design: 60:40 Sand Compost Mix



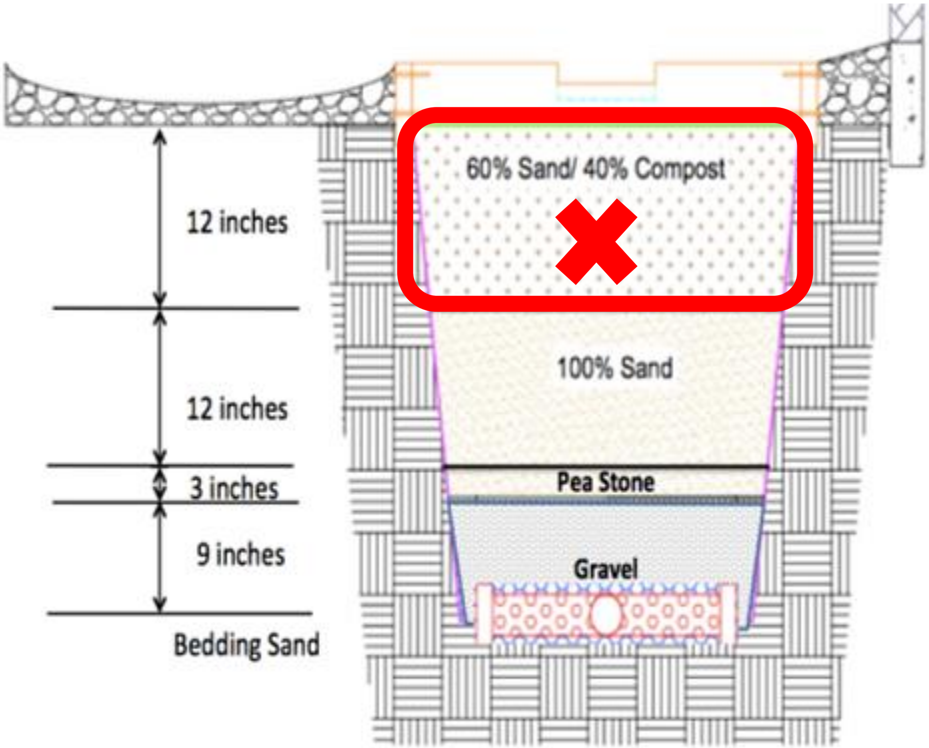
<u>Original Soil Media:</u>

294,880 mg of SRP

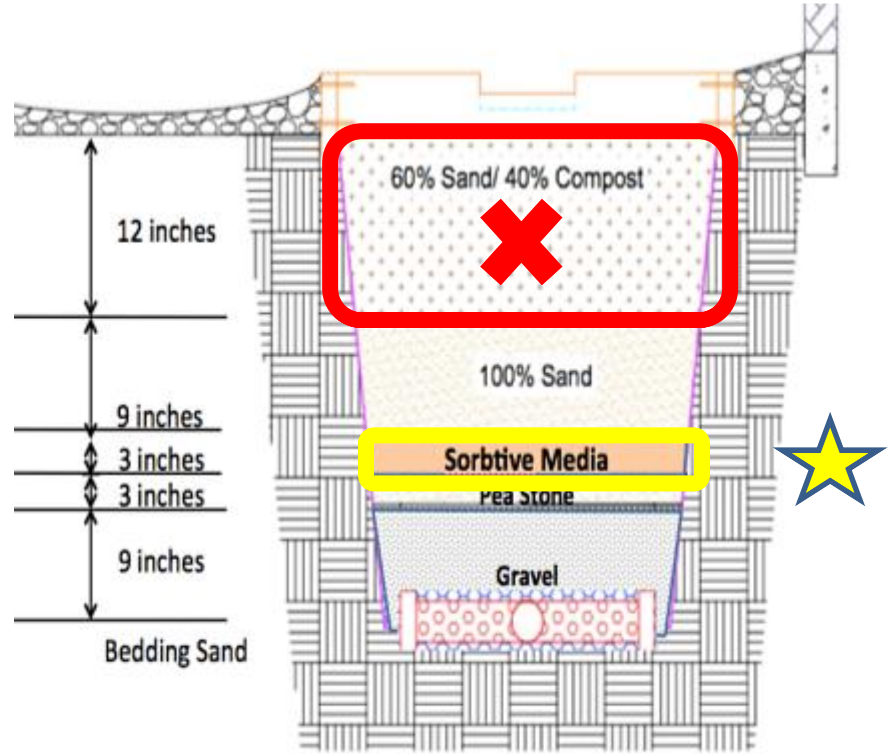
147,052 mg of NO_x

4,439 mg of NH_4^+

Conventional Media Design



Sorbtive Media Design

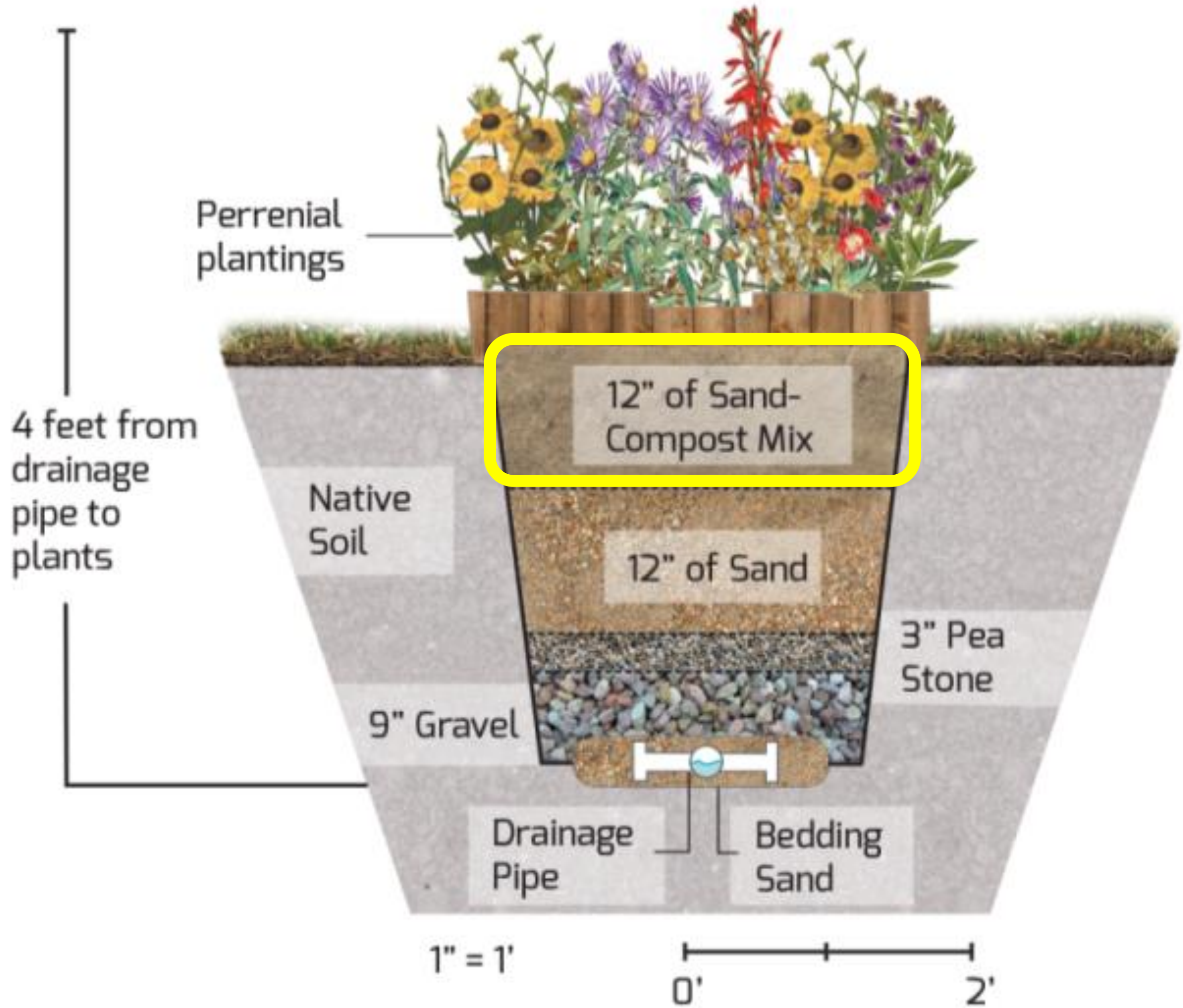


- Stormwater runoff contributed less than 5% of the total SRP load from the cells, with the remainder coming from the compost in the soil media
- NO_3^- mass from stormwater contributed between approximately 10% and 20% of the total load.

Average Outflow Concentrations Compared to the Literature

Parameter	This Study	Literature	Reference
NLP	53 µg L^{-1} (CM)	40 – 800 µg L^{-1} ★	Hunt et al. (2006)
SRP	568 µg L^{-1} (CM)	210 – 670 µg L^{-1} ☑	Geosyntec (2008)
SRP	24 µg L^{-1} (SM)	140 µg L^{-1} ★	Chardon et al. (2005) (Iron Coated Sand)
		< 10 µg L^{-1} ☑	O'Neill and Davis (2011) (WW Treat. Residual)
TKN	376 µg L^{-1} (SM)	1,240 – 1,780 µg L^{-1} ★	Geosyntec (2008)
NO_3^-	227 µg L^{-1} (V2) , 547 µg L^{-1} (V1)	300 – 400 µg L^{-1} ☑	Dietz and Clausen (2006)
TSS	10.20 mg L^{-1} (CM)	15 – 33 mg L^{-1} ★	Geosyntec (2008)

Conventional Bioretention Media Design



Recommended By:

1. Vermont Agency of Natural Resources (2002)
2. Washington State University Pierce County Extension (2012)
3. Center for Watershed Protection

Image Credit: Hurley, S., Zeitz, G.,(unpublished)

Effective Pollutant Removal Requires the Right Soils

<u>Considerations</u>
Textural Class
Infiltration Rate
CEC/AEC
Fe, Ca, or Al
pH

Availability
Cost

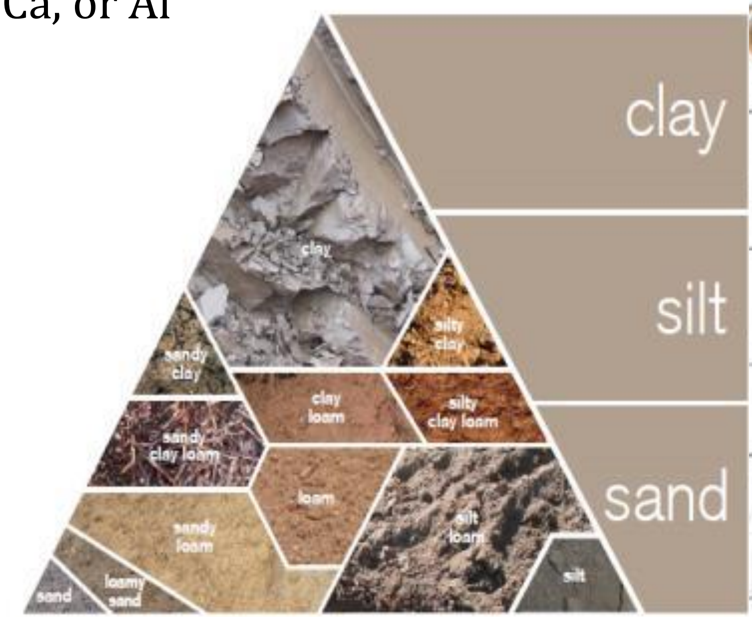


FIGURE 2.2 - SOIL TEXTURE TRIANGLE

Source: University of Arkansas Community Design Center. Image Credit: A. Cording

Media Infiltration Rates

Reference	Infiltration Rate
This study	Modelled Rate at Installation: 131 cm hr^{-1}
Arias et al (2001)	Actual Rate: 463 cm hr^{-1}
Brix et al. (2001)	Actual Rate: 92 cm hr^{-1}
Chen et al (2013)	Actual Rate: 1.3 cm hr^{-1}
Davis et al. (2009)	Recommends > 2.5 cm hr^{-1}
Debusk et al. (2011)	Actual Rate: 11.8 cm hr^{-1}
Dietz and Clausen (2005)	Design Rate: 10 – 13 cm hr^{-1}. Actual Rate: 3.5 cm hr^{-1}
Hatt et al. (2008)	Actual Rate: 26.028 cm hr^{-1} to 232.92 cm hr^{-1} in different treatments
Hunt et al. (2006)	Actual Rate: 7.62 cm hr^{-1} to 38.1 cm hr^{-1}
Li and Davis (2008)	Actual Rate: Reduction from 43 – 164 cm hr^{-1} to 3-11 cm hr^{-1}
Lucas and Greenway (2011)	Vegetated: 27.7 cm hr^{-1} to 59.6 cm hr^{-1}
Thompson et al. (2008)	Actual Rate: 150 to 178 cm hr^{-1} (sand/compost mix)
Washington State University Pierce County Extension (2012)	Recommends > 2.54 cm hr^{-1}

Soil Orders In Hawaii

Prepared by Hue, Ikawa & Yost
Graphics was prepared by Miles Hakoda

Andisol

Kula Series, Maui — Hilo Series, Hawaii

Andisols are soils derived from volcanic ash. The less weathered Kula soil on Maui is quite productive, while the Hilo soil on the Big Island is highly weathered and requires lots of fertilizers for crop production.

Aridisol

Kawaihae Series, Hawaii

Aridisols are soils of the arid areas or soils with high salt content. The Kawaihae soil of the Big Island has features of an arid area of light color, low organic matter, and shallow depth.

Entisol

Jaucas Series, Maui

Entisols are least-developed soils showing only a weak surface development. The calareous Jaucas soil on Maui is an example with sandy texture, and excessive drainage.

Histosol

Papai Series, Hawaii — Alakai Series, Oahu

Histosols are organic soils with a high organic matter content in the surface horizon. The Papai soil on the Big Island has lost almost all of the surface organic matter (OM), but the Alakai soil atop Mt. Kaala on Oahu is high in OM.

Inceptisol

Kolekole Series, Oahu

Inceptisols are soils showing minimal development of soil horizons. The Kolekole soil on Oahu is an example.

Mollisol

Kawaihapai Series, Oahu — Makawele Series, Kauai

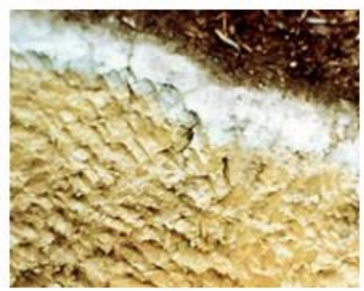
Mollisols are fertile soils with high organic C and high base saturation. Although the Kawaihapai soil on Oahu is dark, the Makawele soil on Kauai is red because of Fe oxides.

Oxisol

Halii Series, Kauai

Oxisols are the most weathered soils of the tropics with low nutrient holding capacity and high Fe and Al oxides. The Halii soil on Kauai is an example.

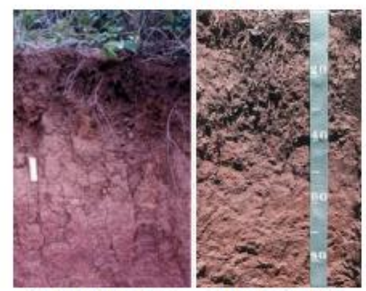
Spodosol-like soil



Oahu

Spodosols are soils with leached Al, Fe, and organic materials in the subsoil, showing a distinct layer.

Ultisol



Alaeloa Series, Oahu — Haiku Series, Maui

Ultisols are highly weathered infertile soils with clay accumulation in the subsoils. Examples are Alaeloa soil on Oahu and Haiku soil on Maui.

Vertisol

Lualualei Series, Oahu

Vertisols are soils that shrink when dry and swell when wet. They usually occur in valleys with poor drainage. They are fertile, but pose severe limitations for roads, housing, and related uses. The Lualualei soil on Oahu is an example.

Commercial Bioretention Research Site: Kane‘ohe, Hawai’i

- Construction Complete: November 2015
- SRP Removal w Sorption: Engineered Soil Blend: No Compost
- NO_3^- Removal with Extended Retention > 6 hrs
- Exploratory Monitoring: November 2015 - 2016

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Fossil fuel
Emission

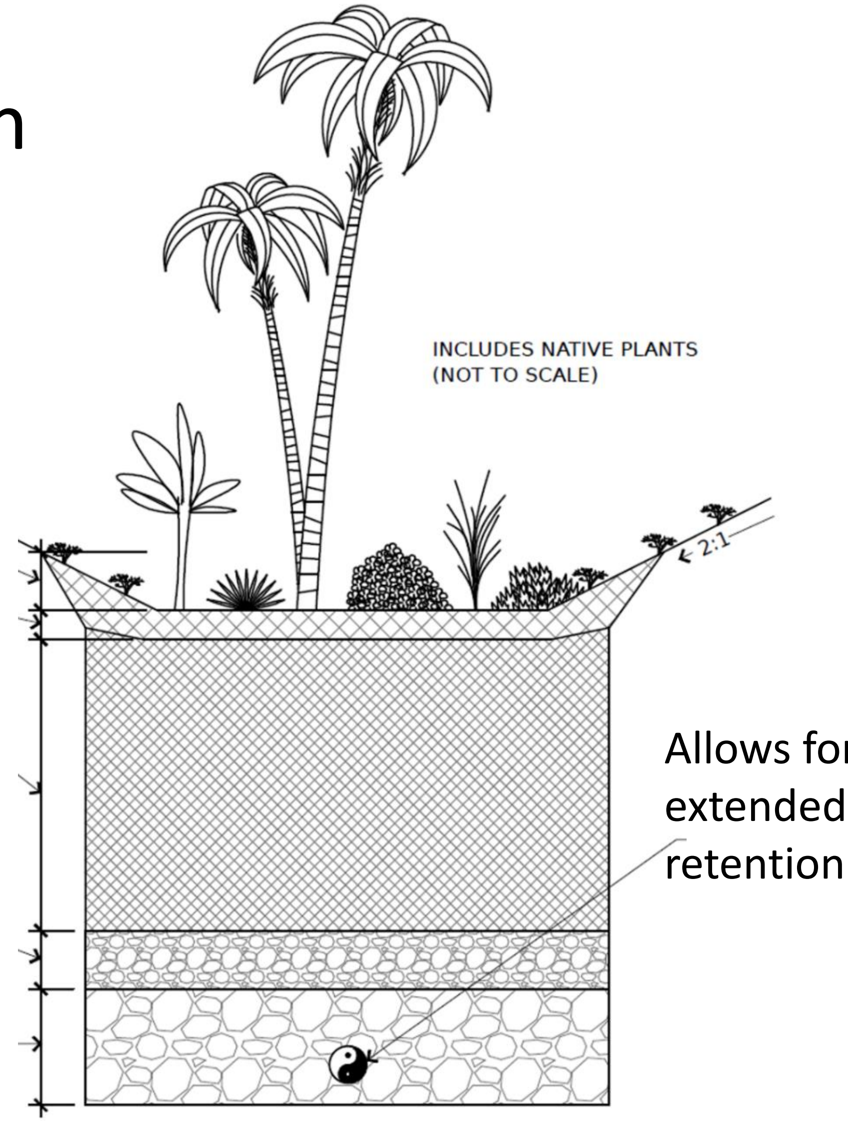
Effective
Bioretention (LID) Design

Native Soil Blend:
Target Infiltration Rate 2.5 - 100 cm/hr
High Mineral Contents (Ca, Fe)

Extended Retention, NO_3^- Removal:
Target Retention Time > 6hrs

Native Plants:
Target >75% Cover
Target Root Depths 1 to 4 ft

- No Compost
- Mulch or Stone Top Dressing



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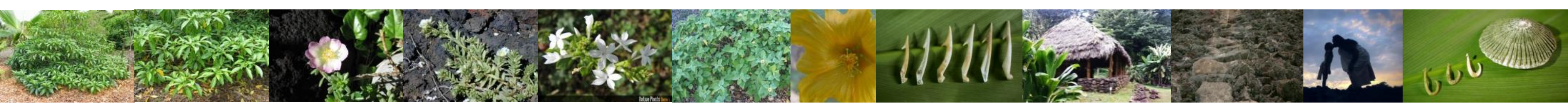
Future Research

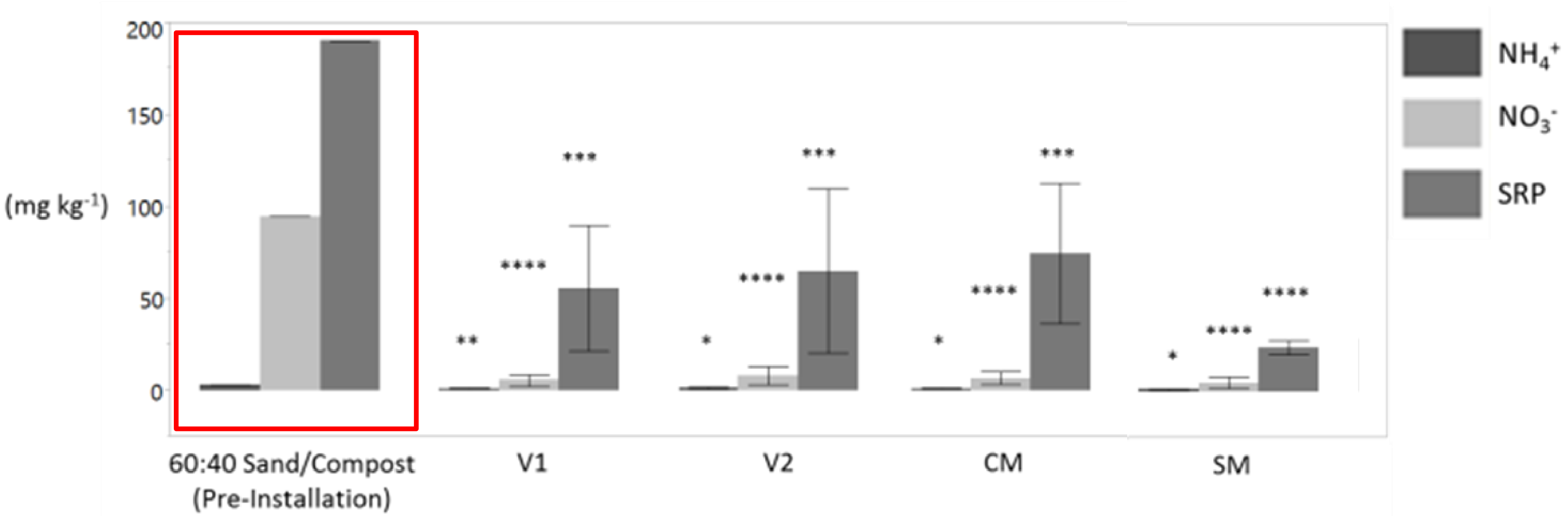
1. Labile carbon for efficient nitrate (NO_3^-) removal

2. Develop Local Soil blends – getting the right mix of minerals and permeability

3. Planting pallets – quantifying pollutant removal loads of vegetation given a certain incoming load, maximizing pollutant removal, root depth, surface area, survivability and aesthetics



Decrease in Soil Media Nutrients Over First Two Years

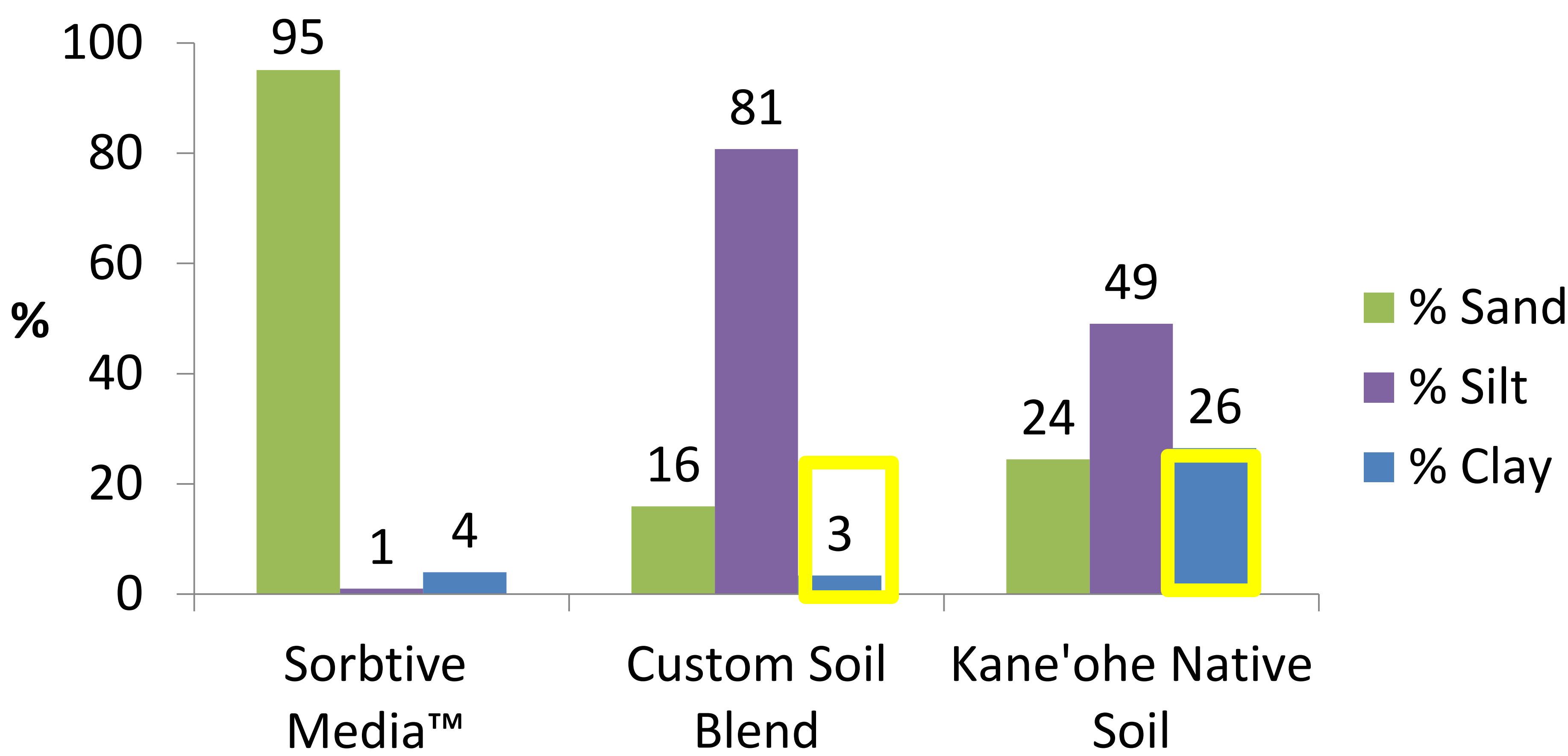


NH_4^+, NO_3^-, and SRP significantly decreased from the original pre-installation mix after two years, in all treatments.

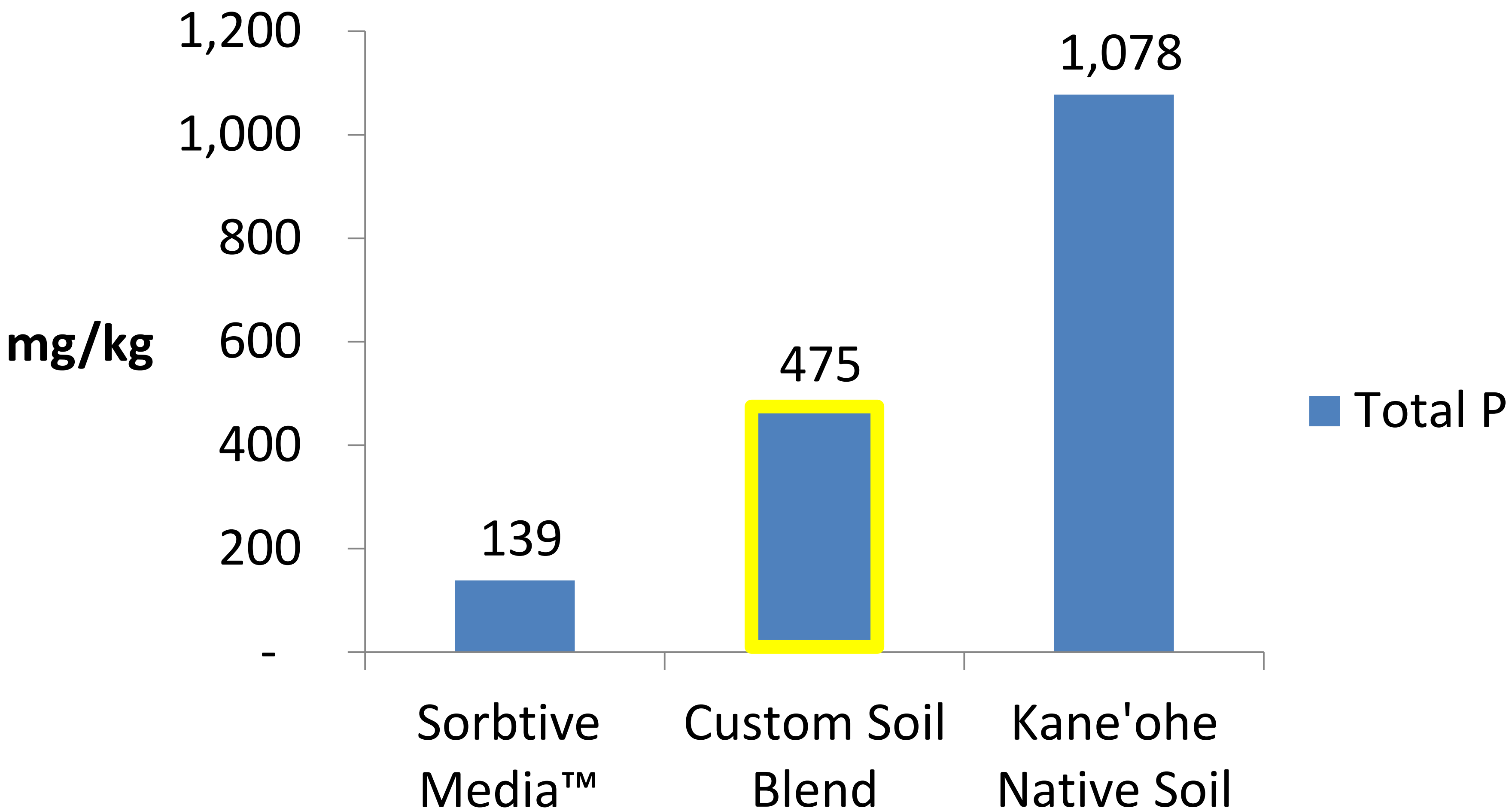
SRP decreased by between 66% (201 g) and 87 % (257 g).

NO_3^- decreased between 92% (135 g) and 96% (141 g).

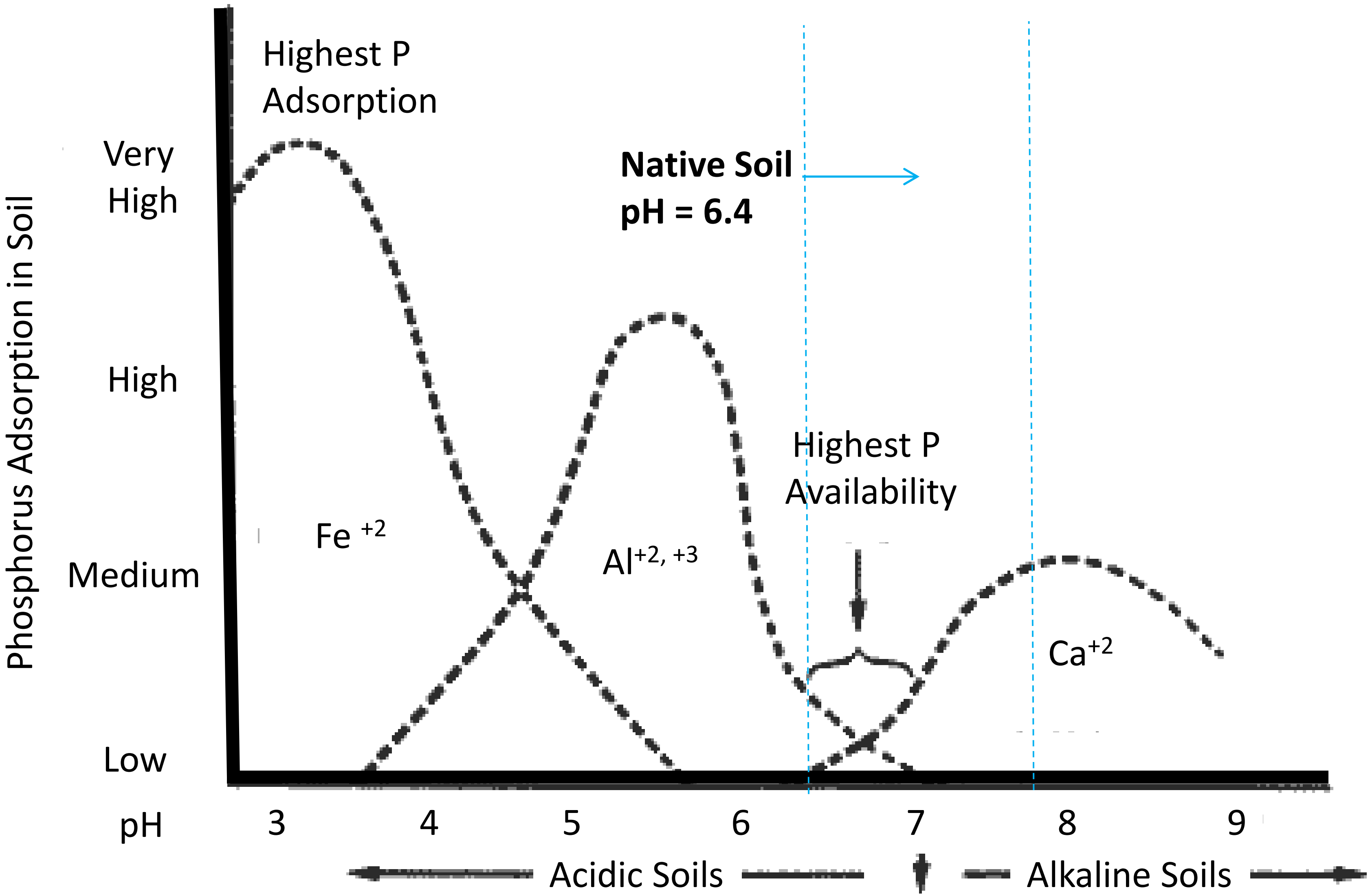
Design Soil Drainage Characteristics to Achieve Target Infiltration Rate



Design Soil Media to Limit Total P



Test pH to Target Mineral Content for Phosphorus Sorption



Increase Mineral Content to Achieve Target P Sorption